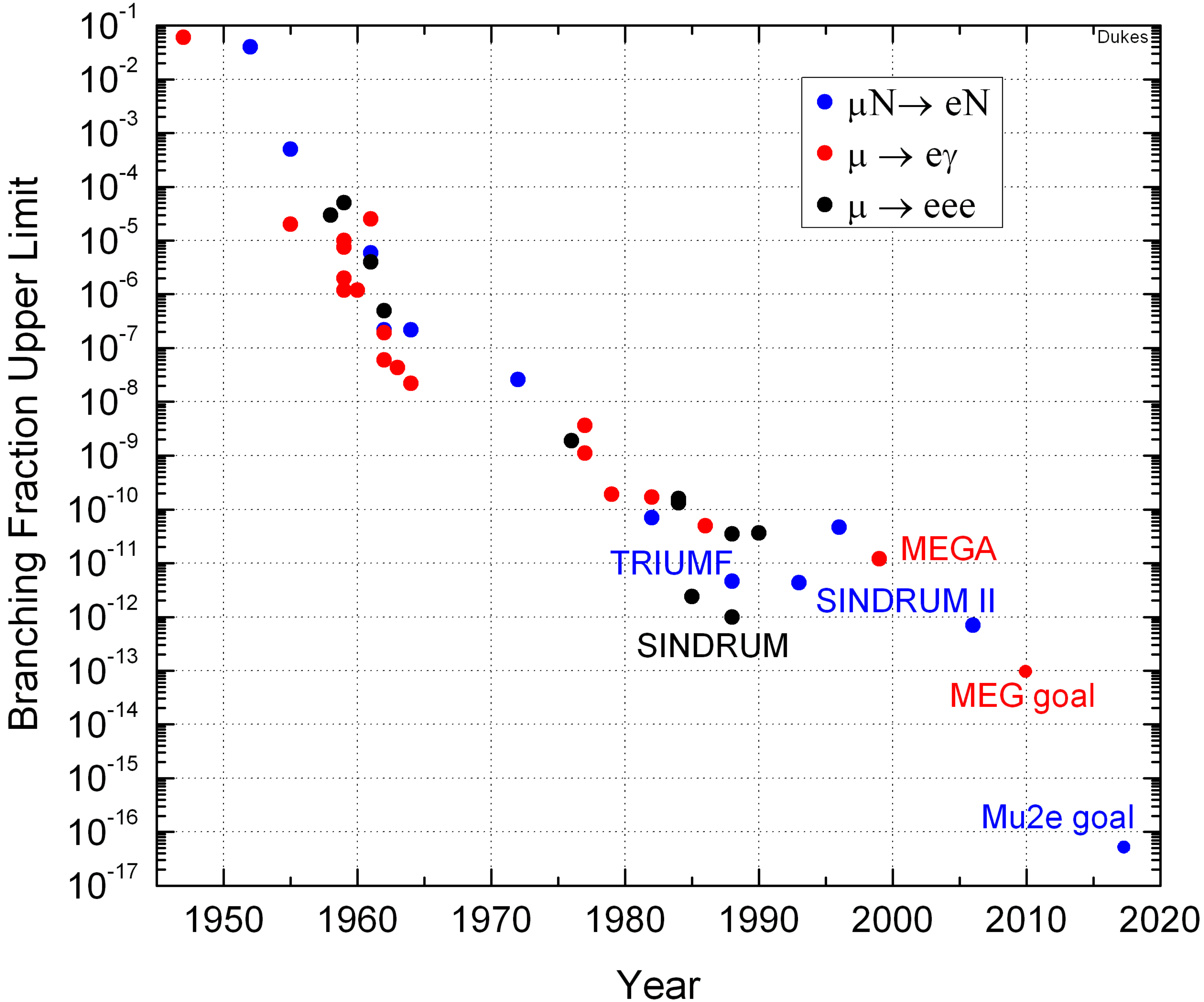
The Mu2e Experiment
A High-sensitivity Charged Lepton Flavor Violating Search at Fermilab

For the Mu2e Collaboration
Kevin Lynch
Boston University
INPC, Vancouver, BC, Canada
July 4-9, 2010

A brief roadmap to this talk...

- Lepton Flavor Violation
- Primary backgrounds to muon conversion
- The design of Mu2e

The mystery of lepton flavor has been with us for many decades



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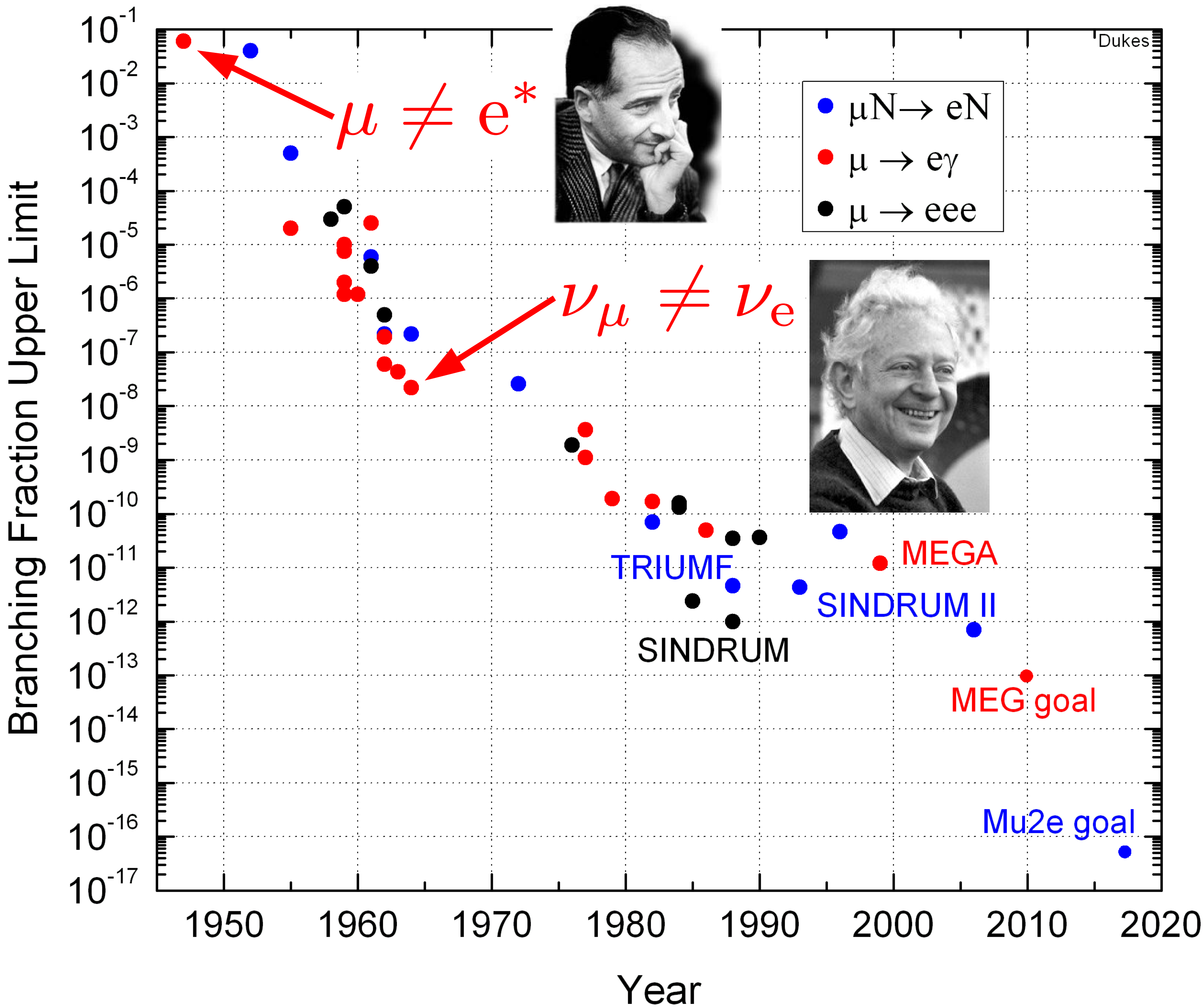

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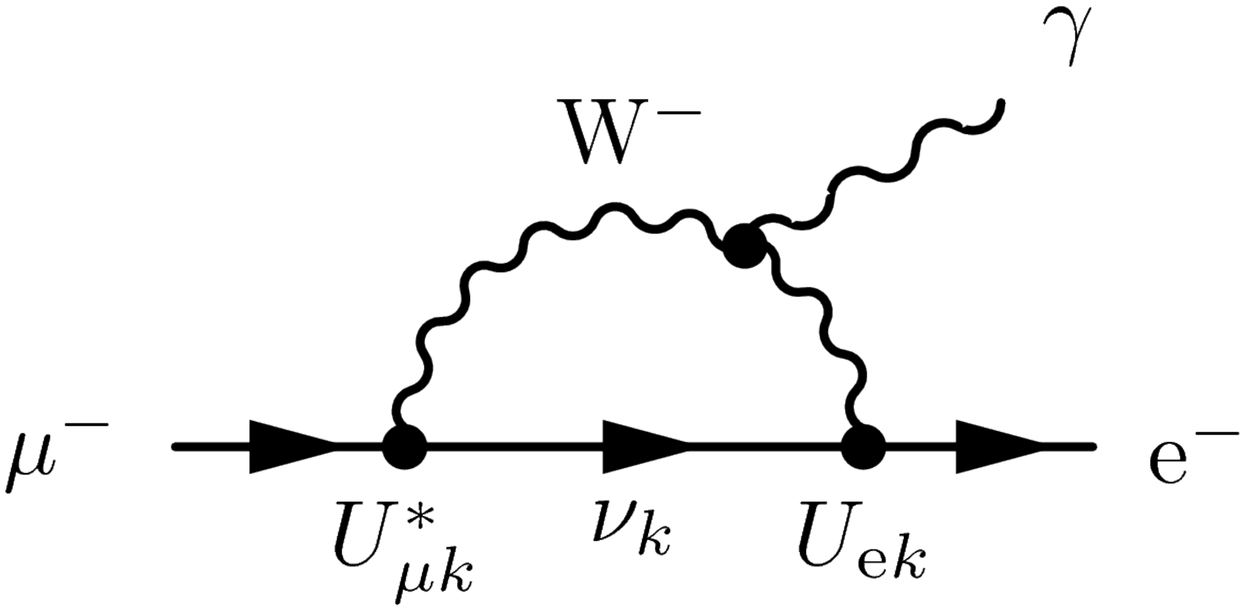

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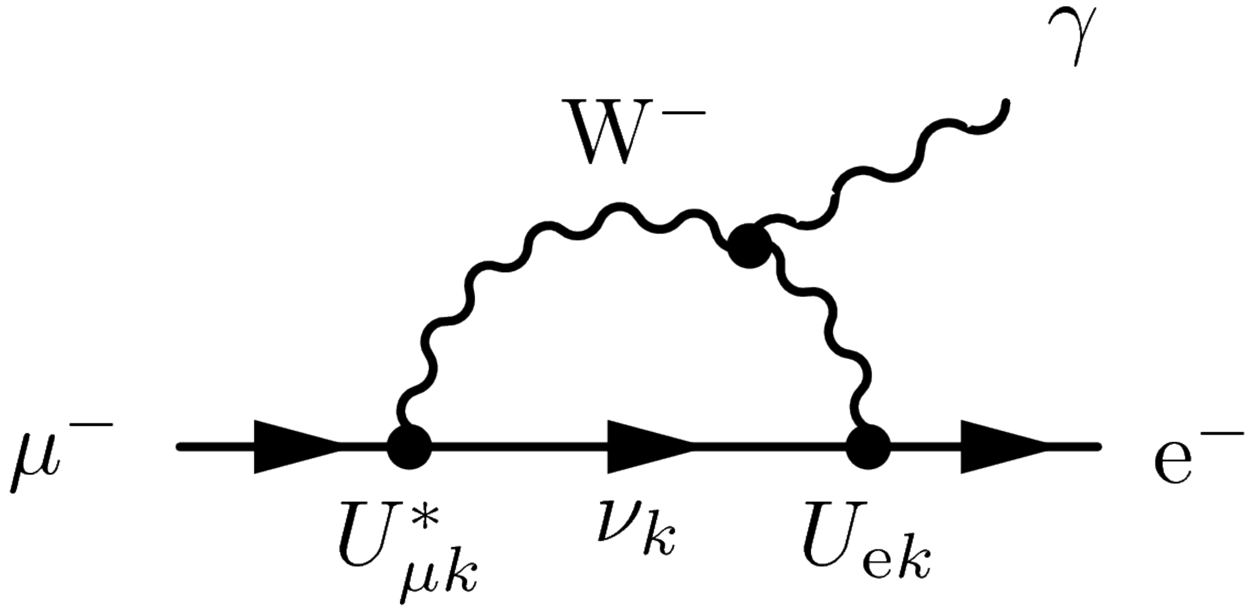

However, the predicted SM rates are unobservably small:

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{ek} \frac{\Delta m^2_{1k}}{M^2_W} \right|^2 < 10^{-54}$$

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The discovery of Weak scale SUSY at LHC would imply observable cLFV rates

$$R_{\mu\mathrm{e}} \sim 10^{-15}$$

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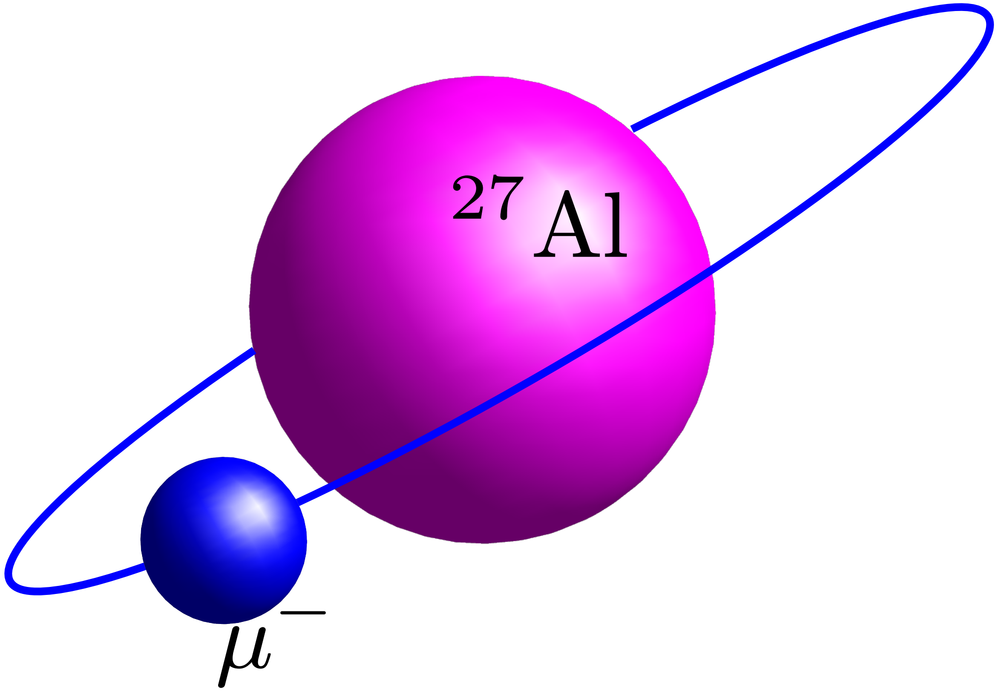

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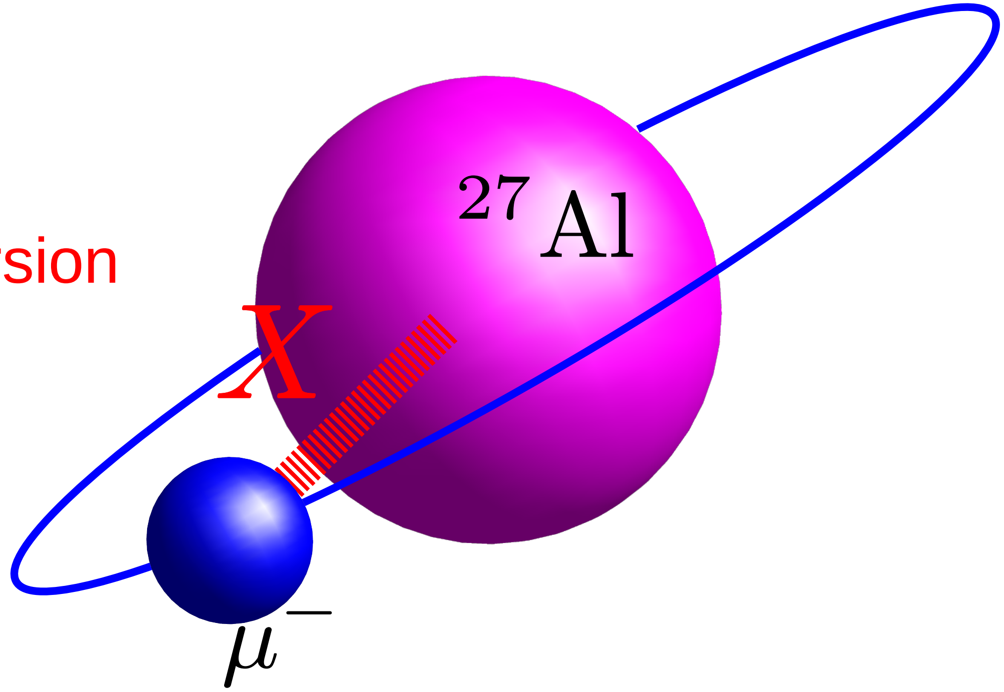

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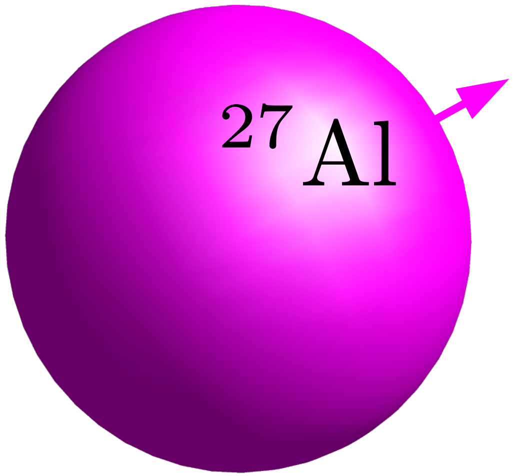

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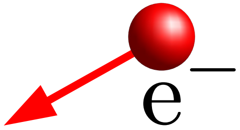

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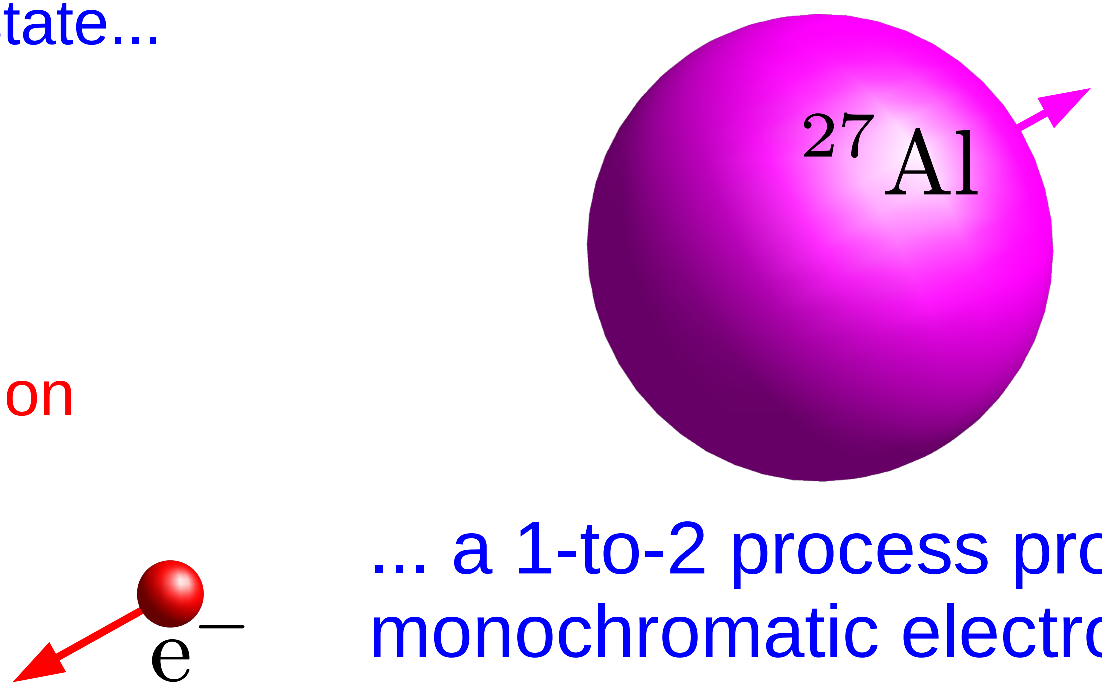

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$$E_\mathrm{e} = m_\mu - E_{1s} - E_{A(Z,N)}$$

$$E_\mathrm{e}(^{27}\mathrm{Al}) = 104.97\,\mathrm{MeV}$$

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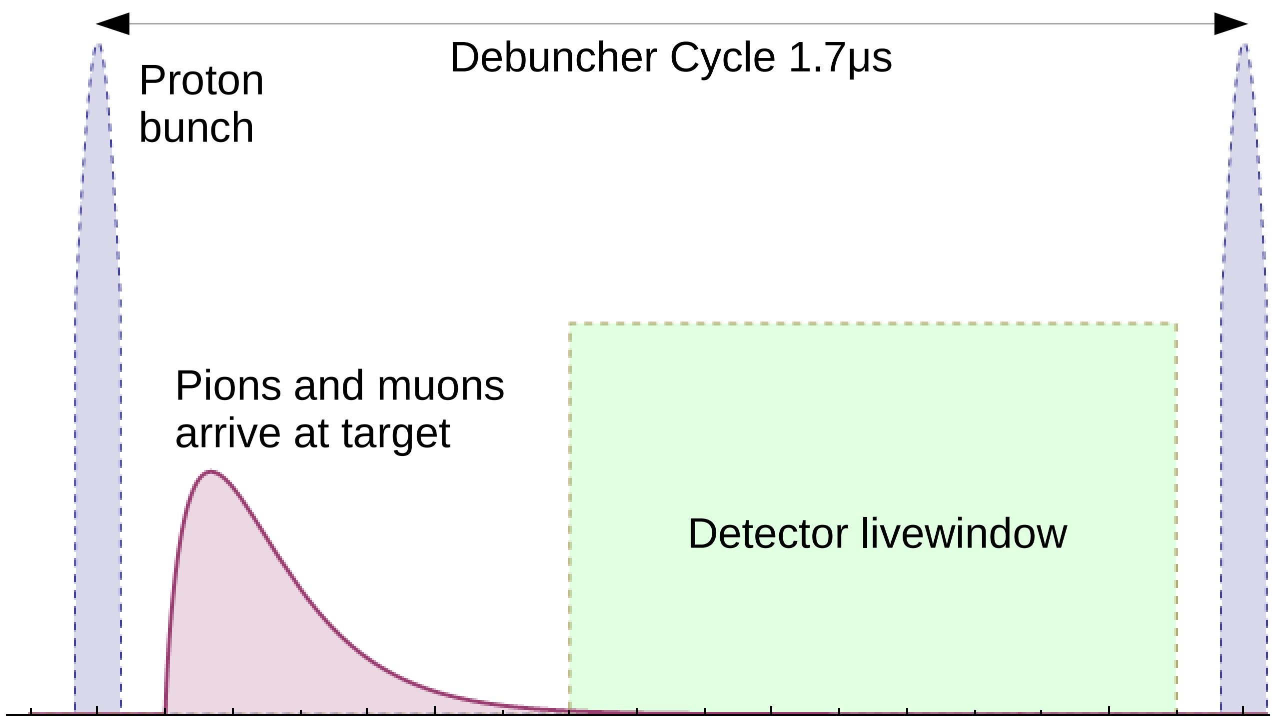

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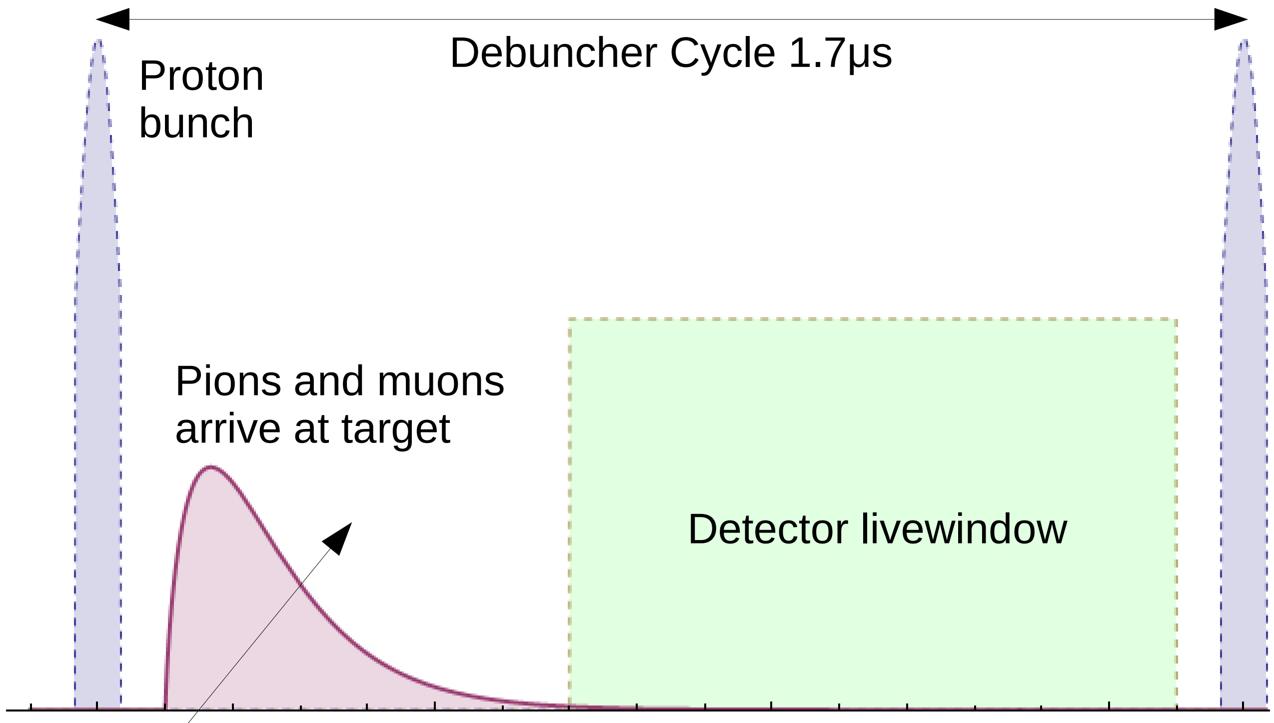

Prompt: Radiative Pion Capture with pair production

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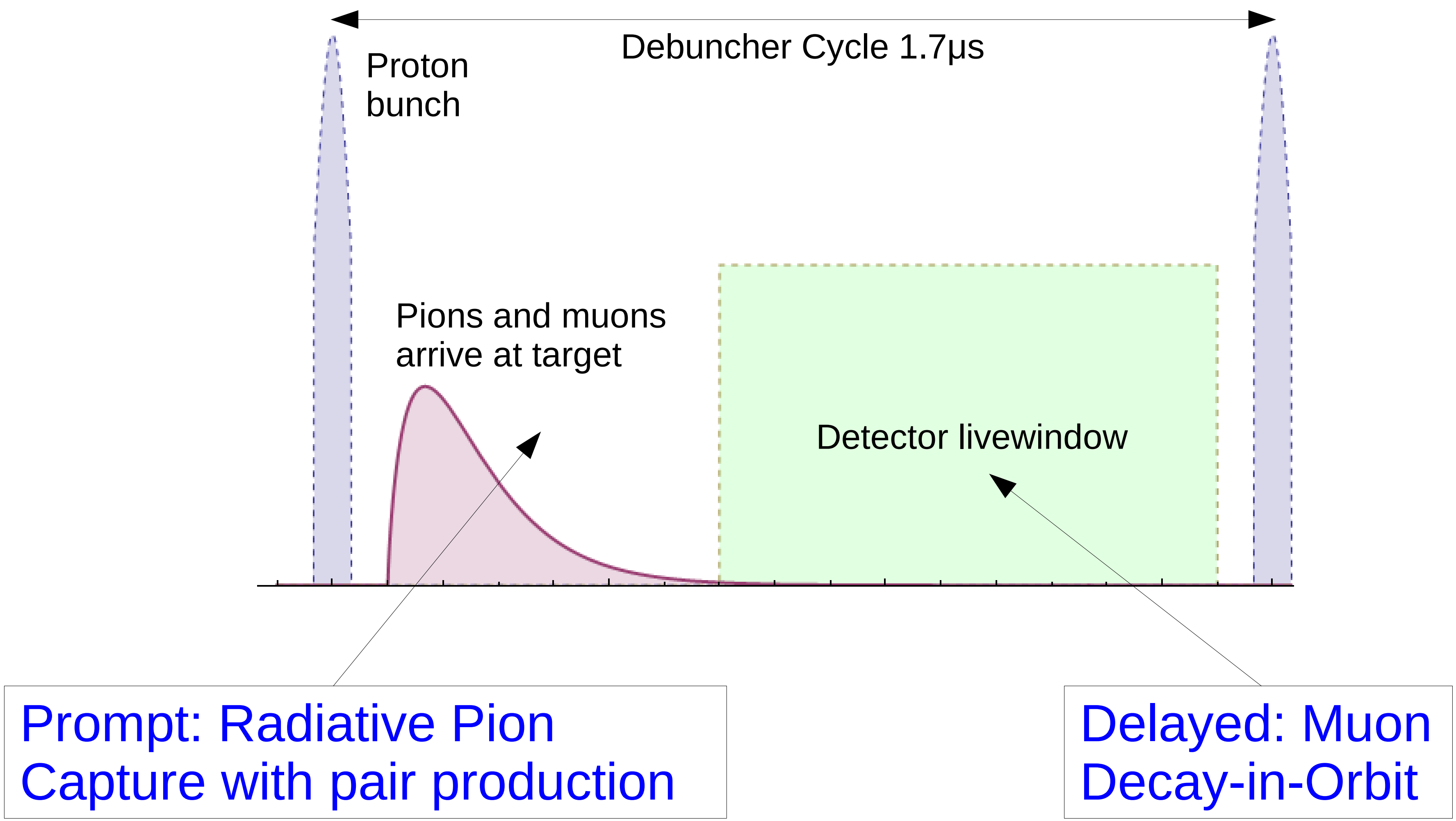

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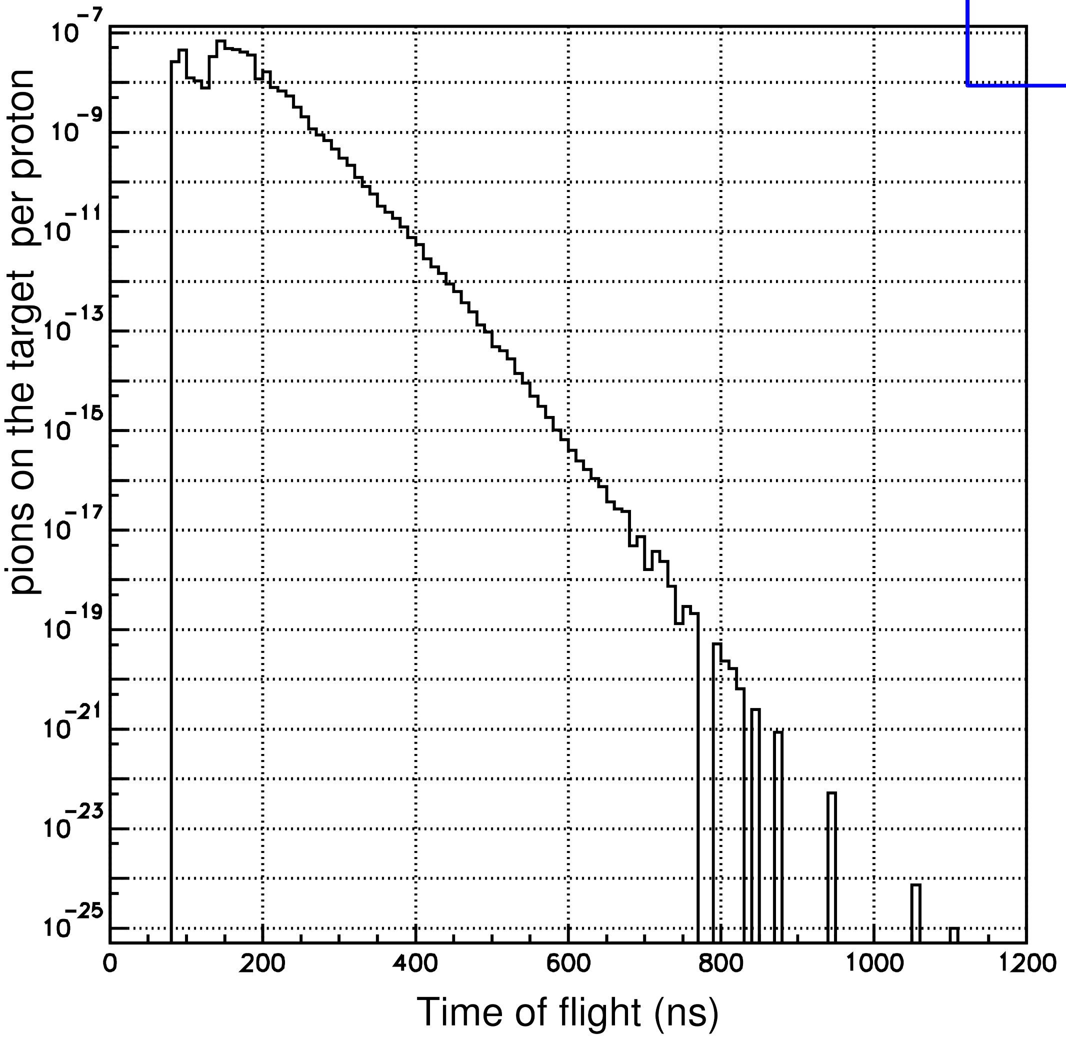

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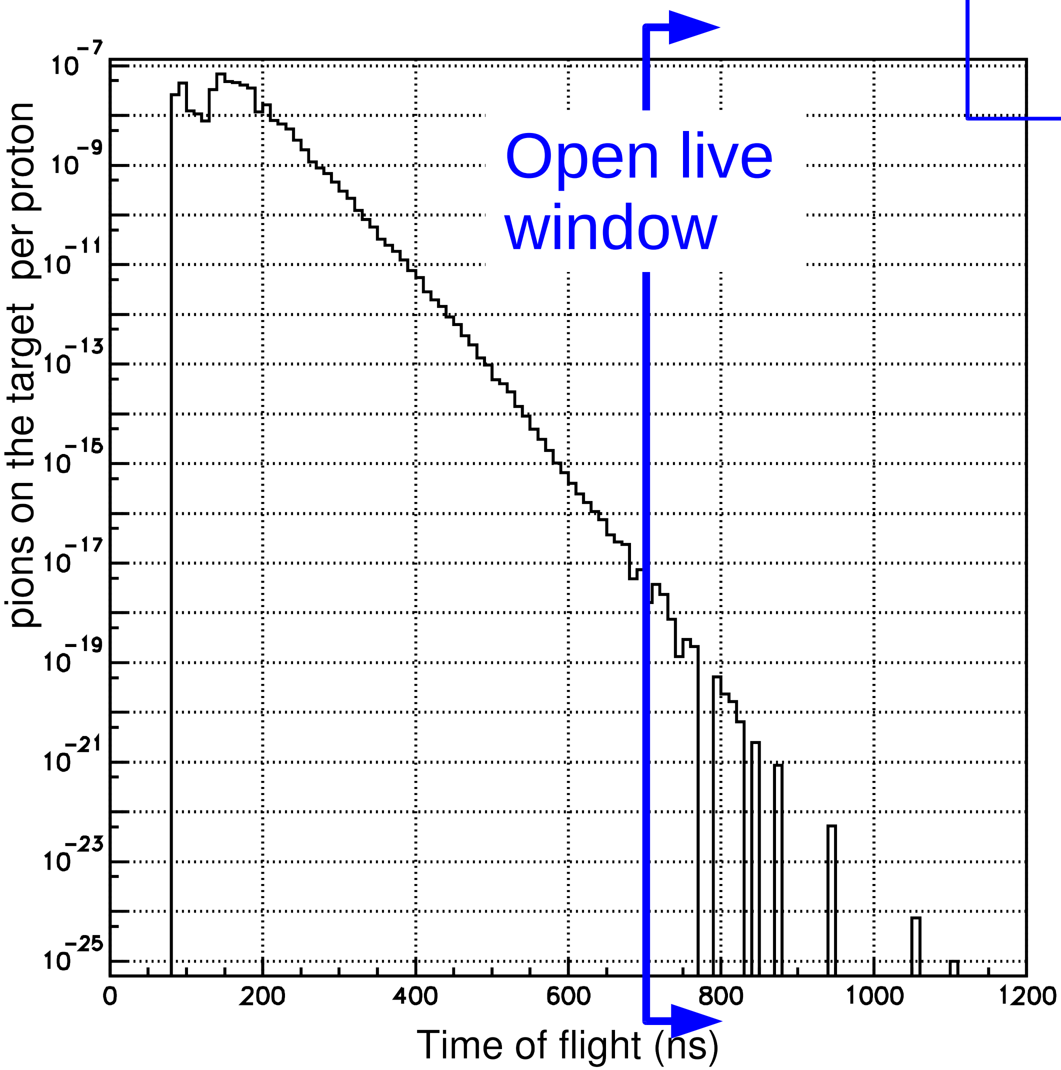

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This (and other) prompt backgrounds are eliminated by keeping the DAQ dead until the background rate has fallen below some threshold.

Decay-in-Orbit is the major source of delayed background in the live window

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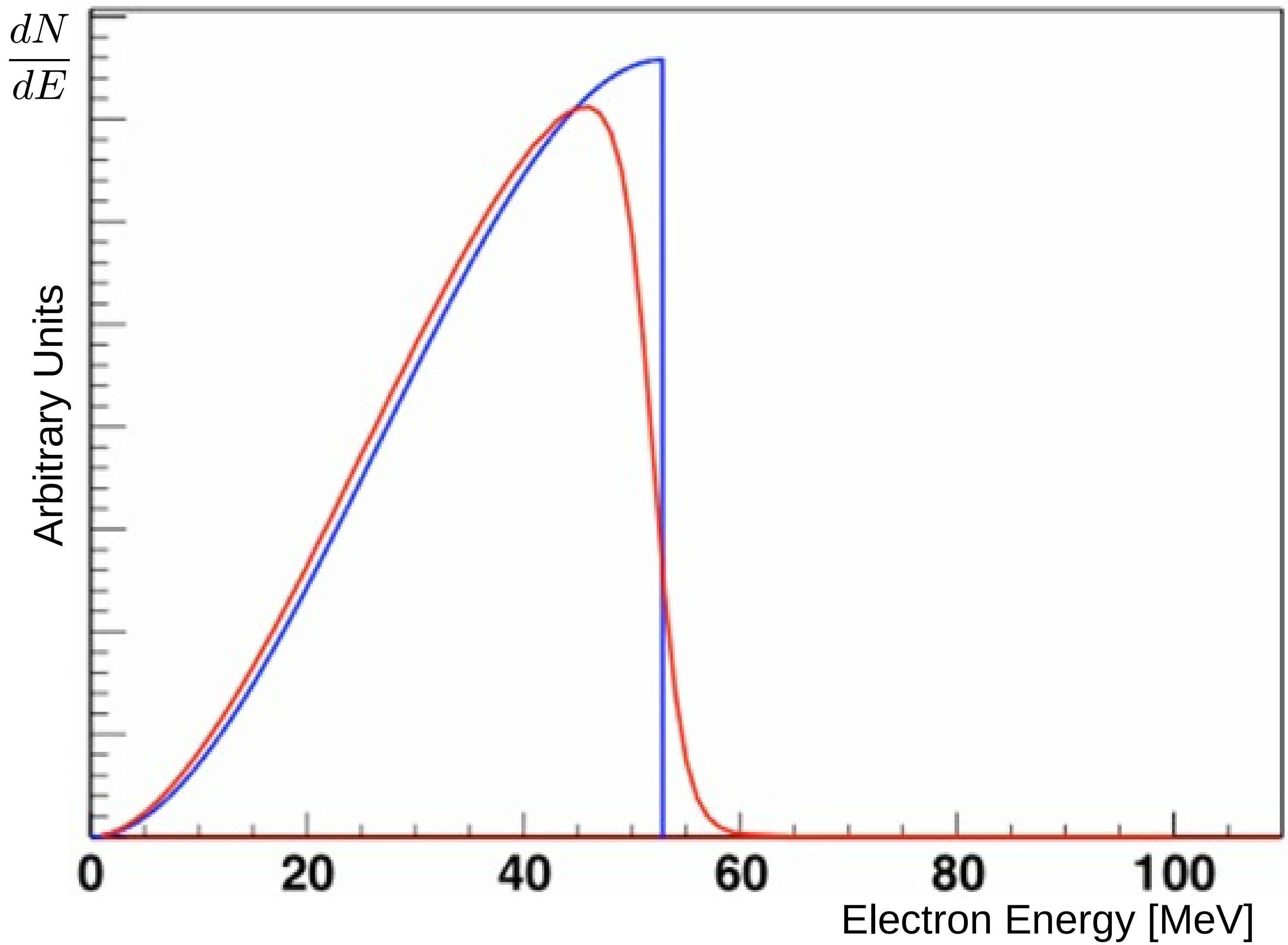

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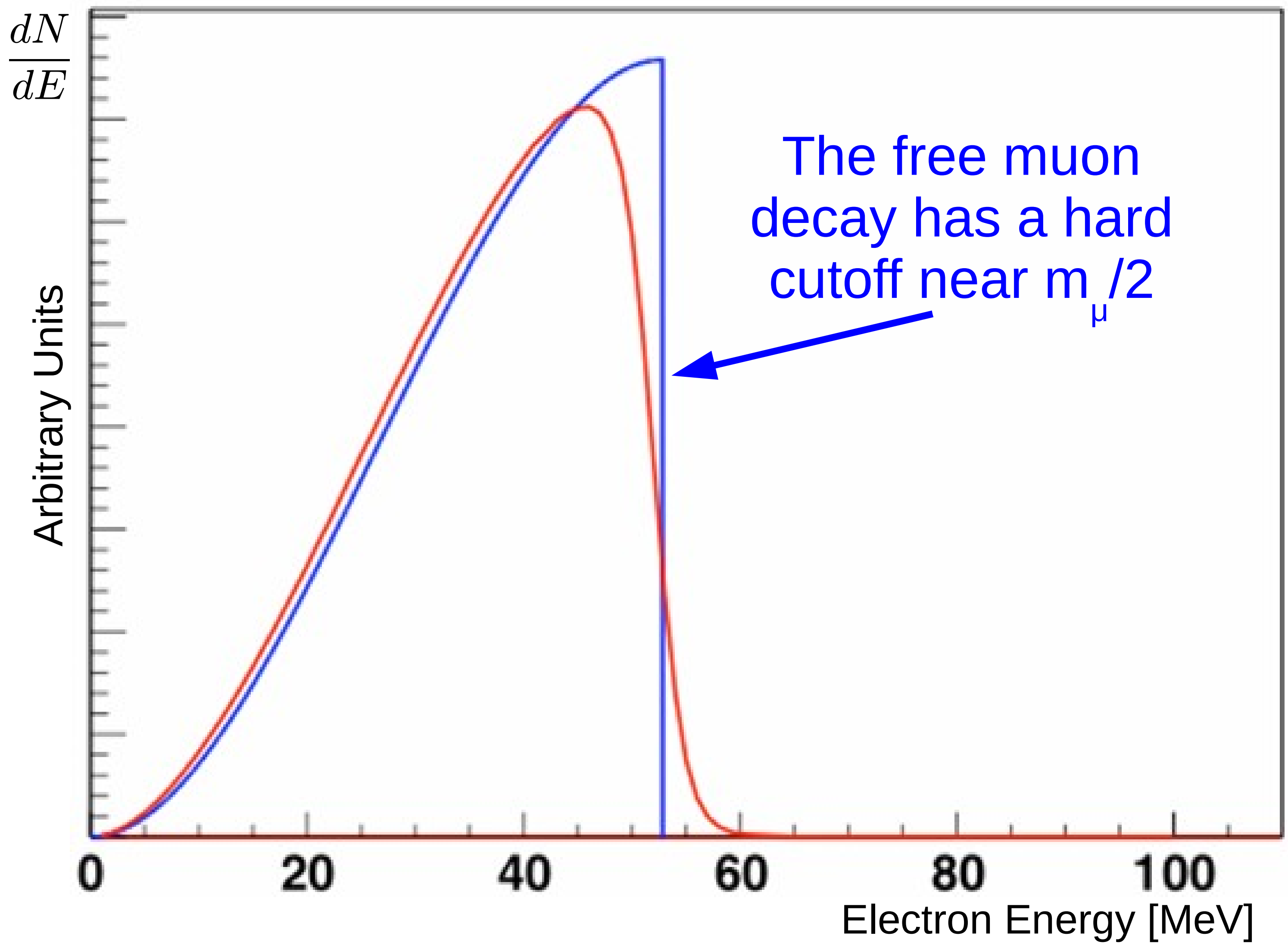

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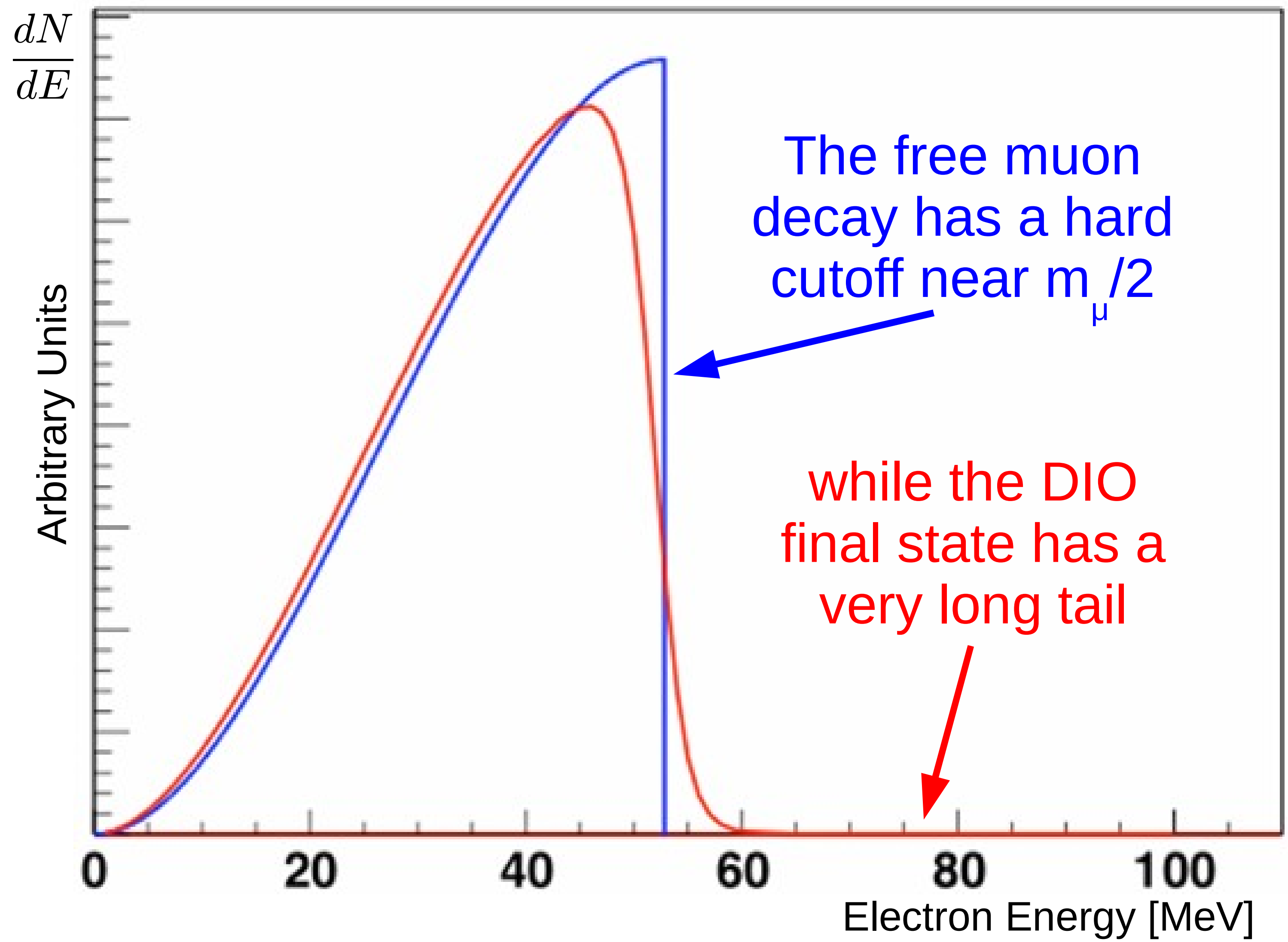

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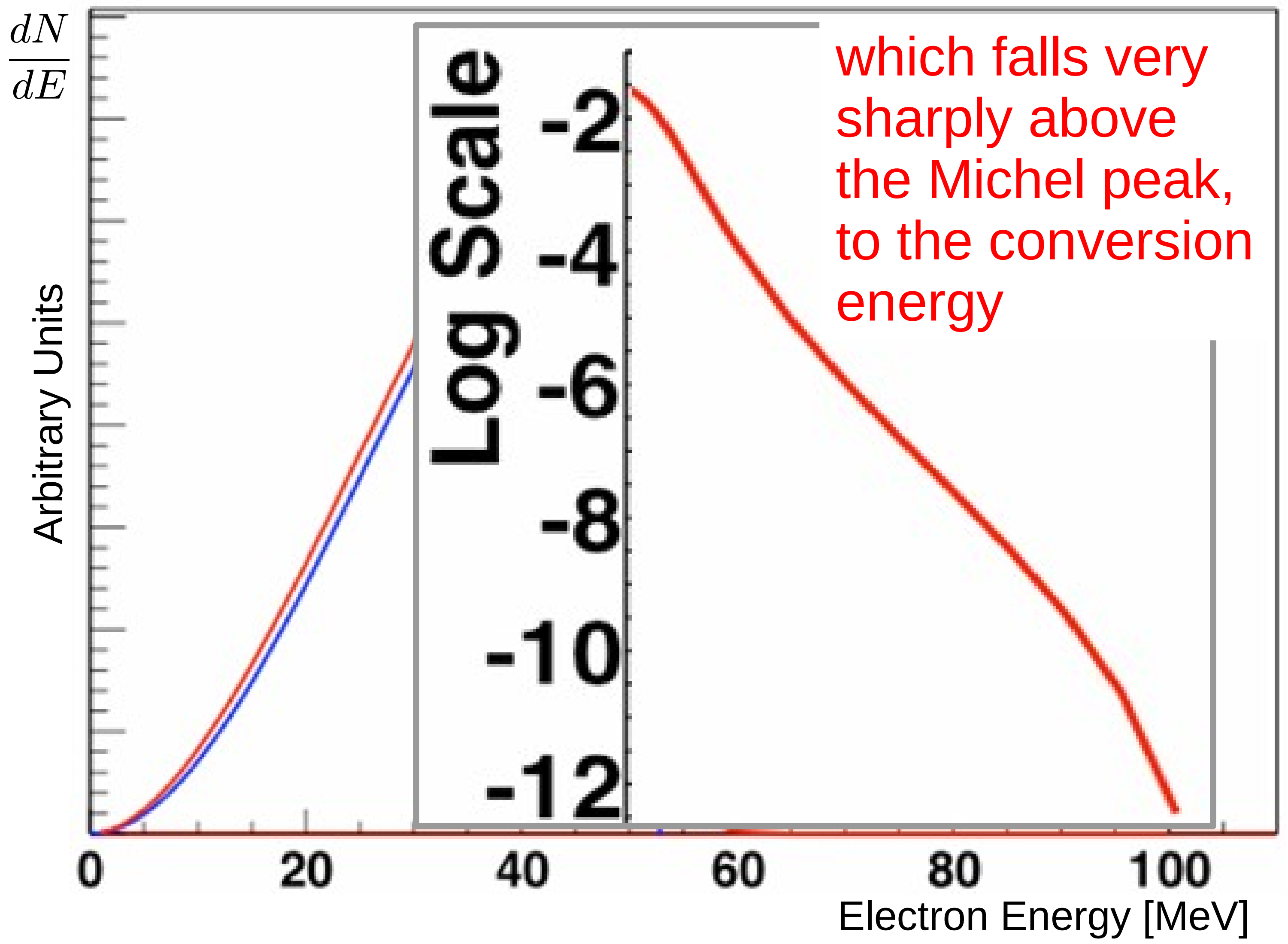
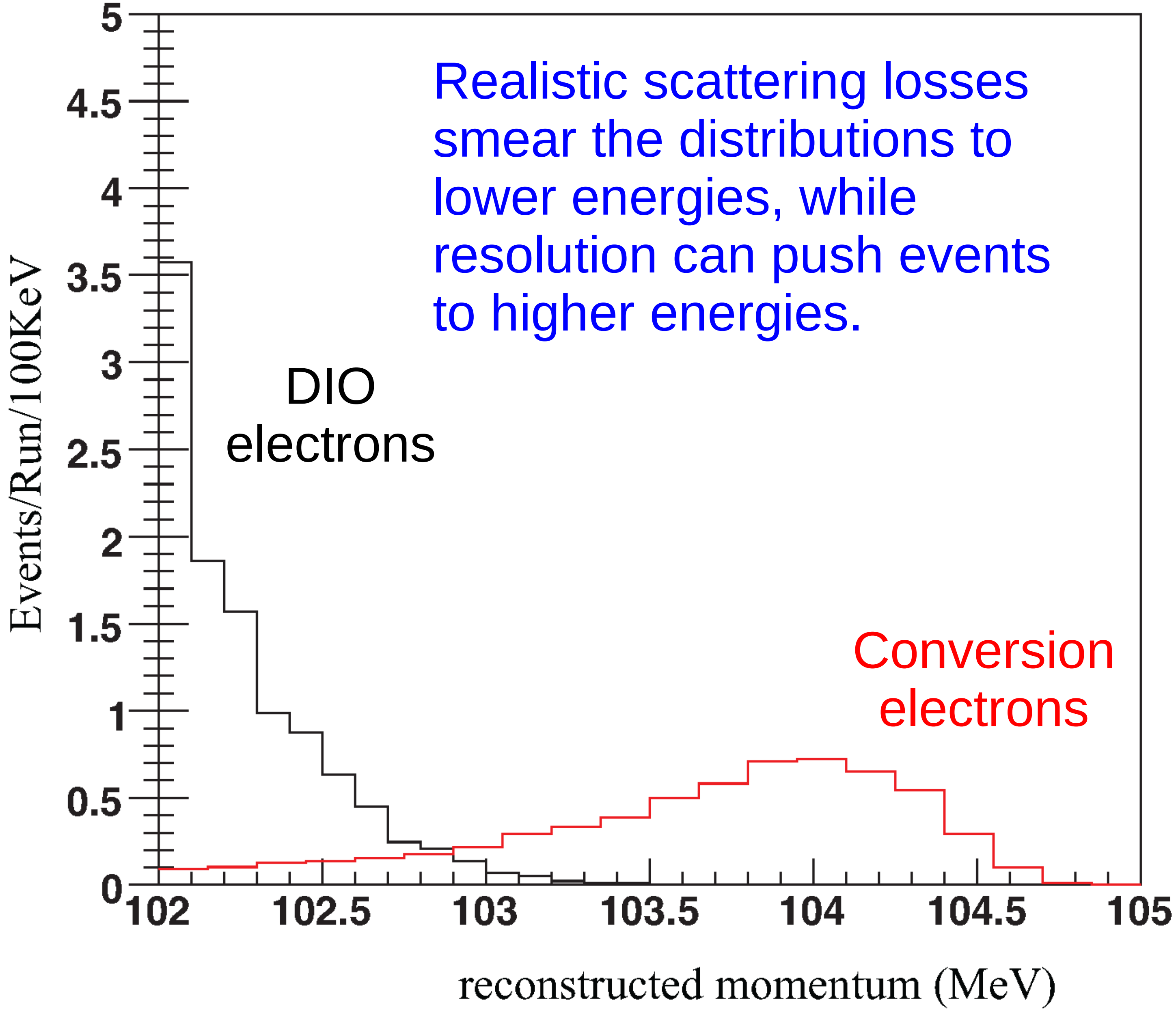


An experimental reality check



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This is a factor 10^4 improvement on the current limit!

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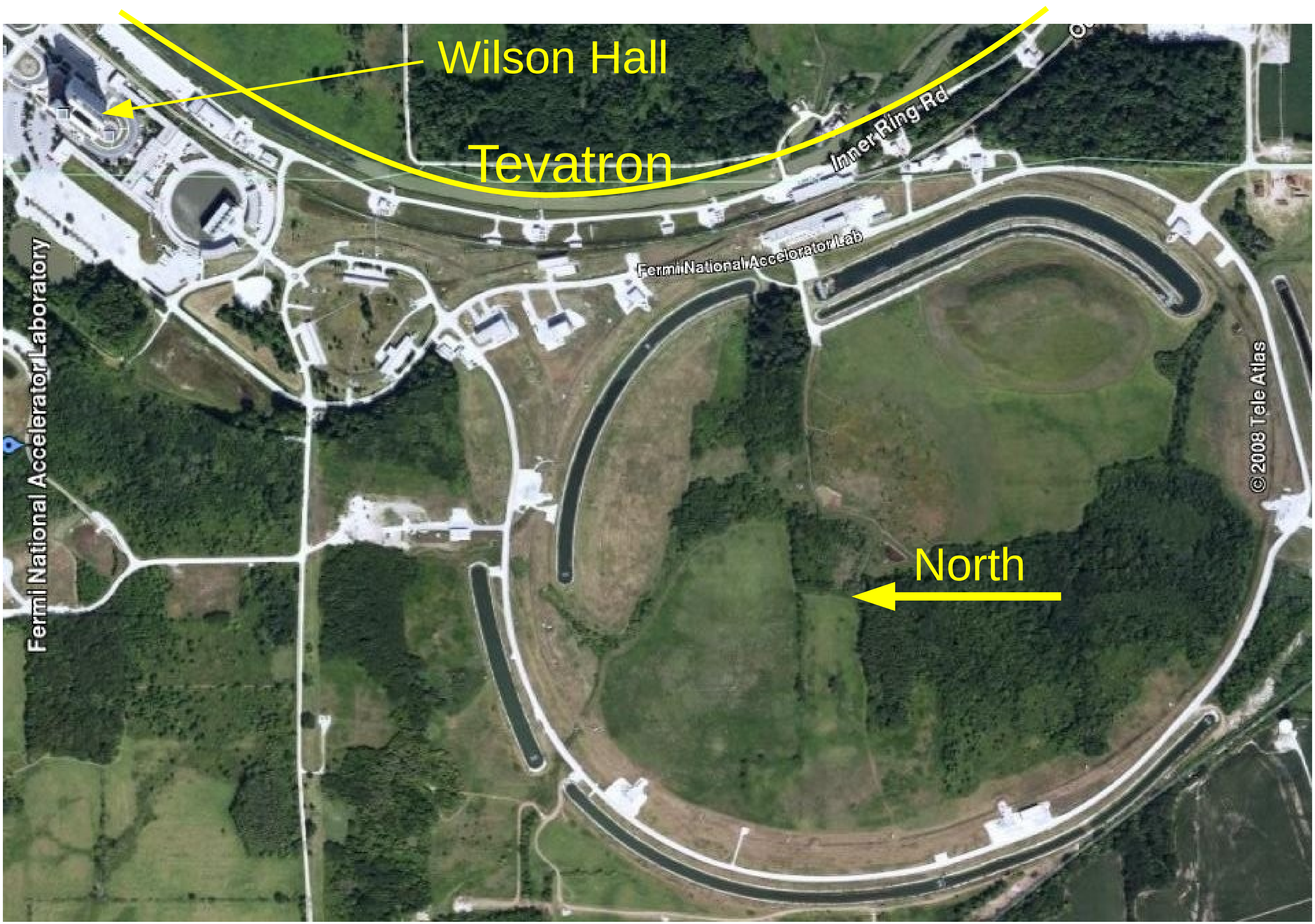

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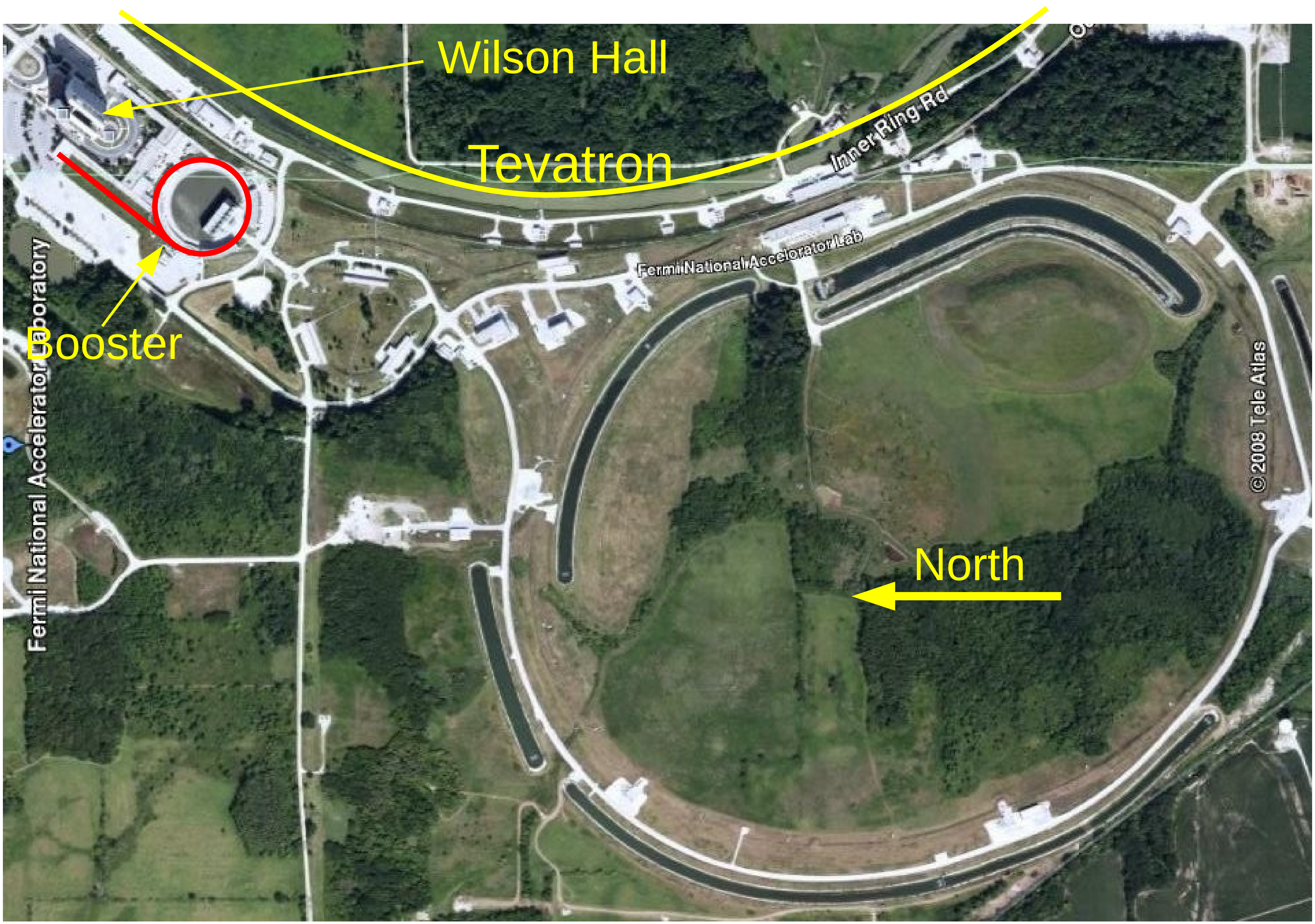

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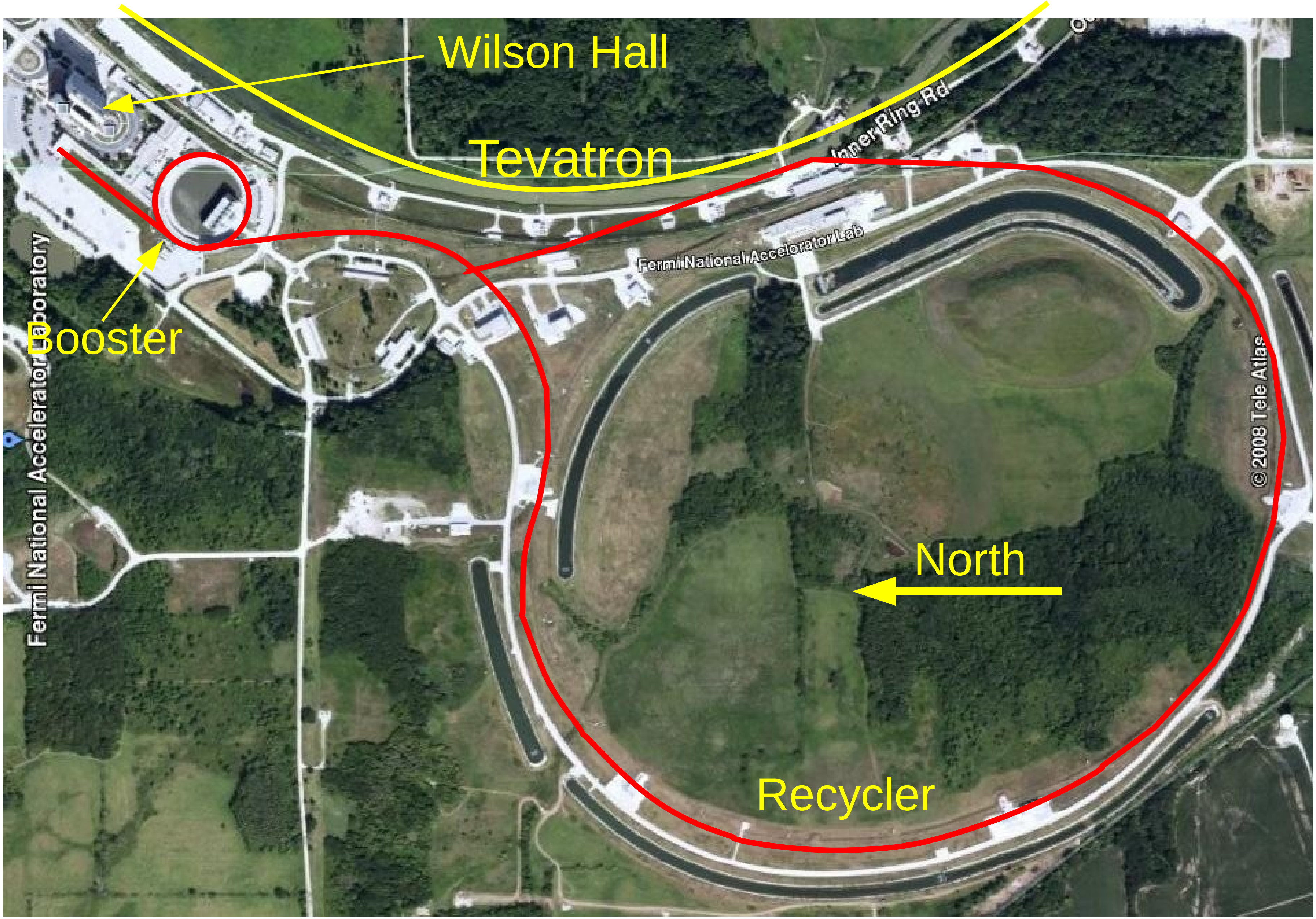

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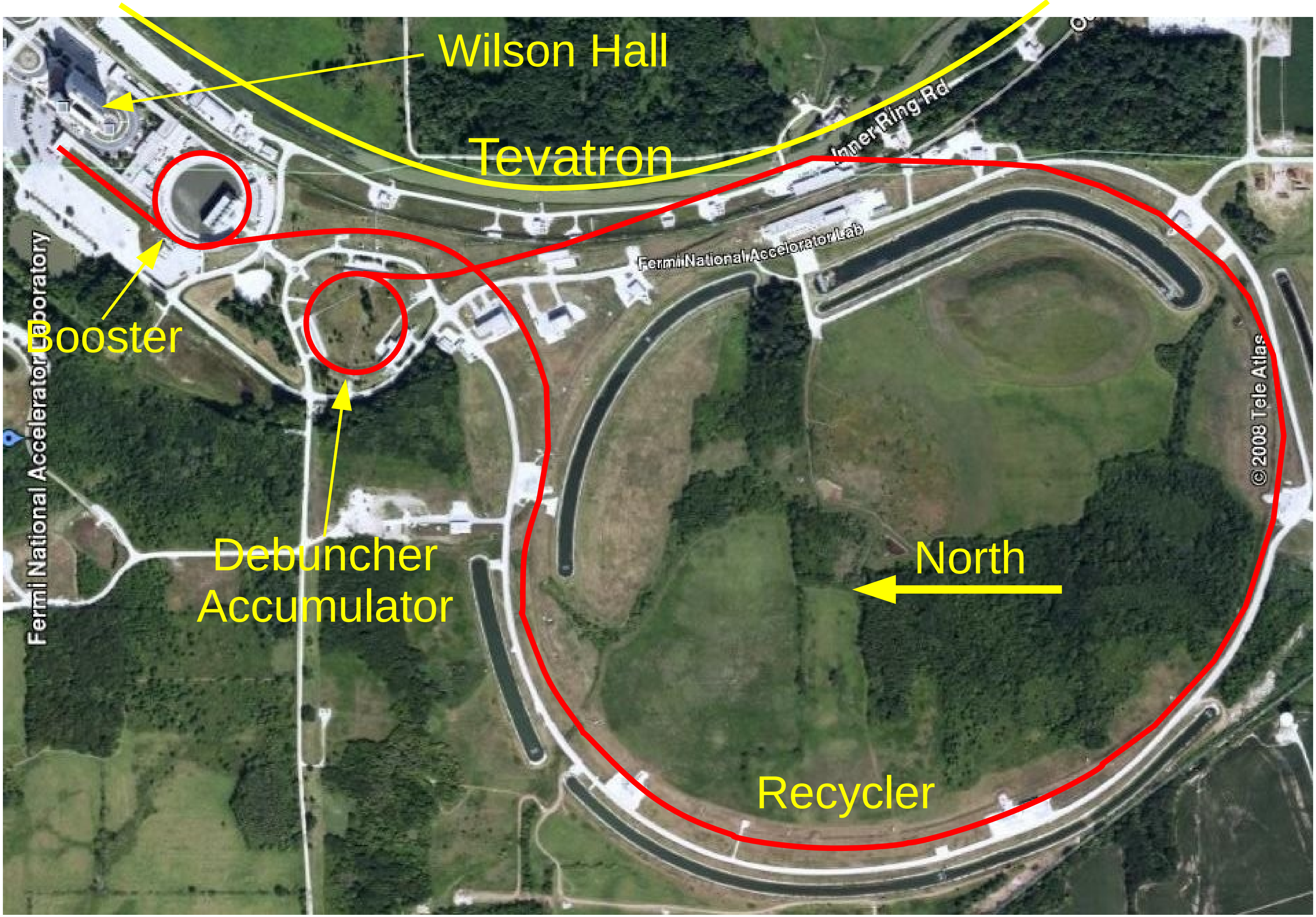

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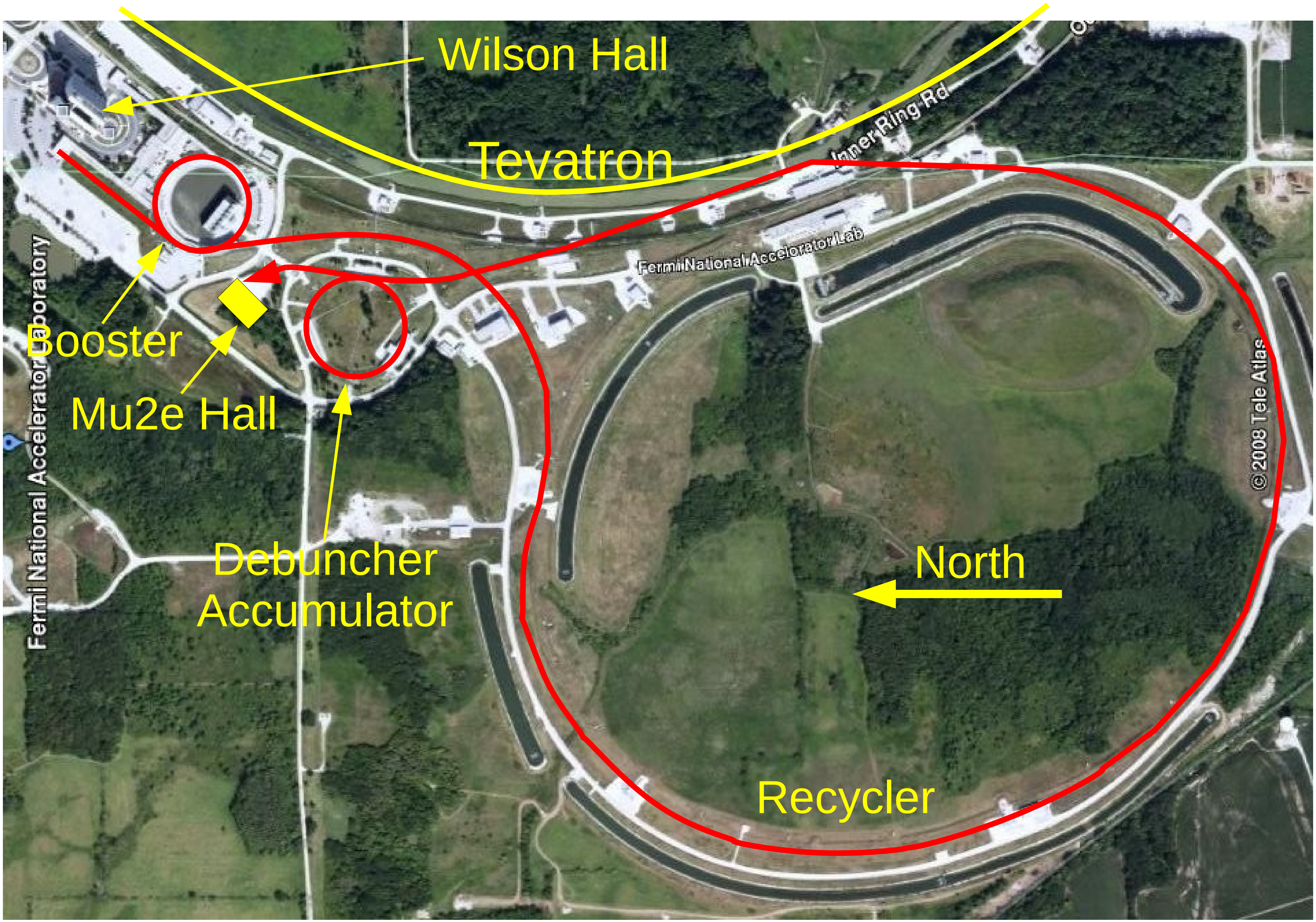

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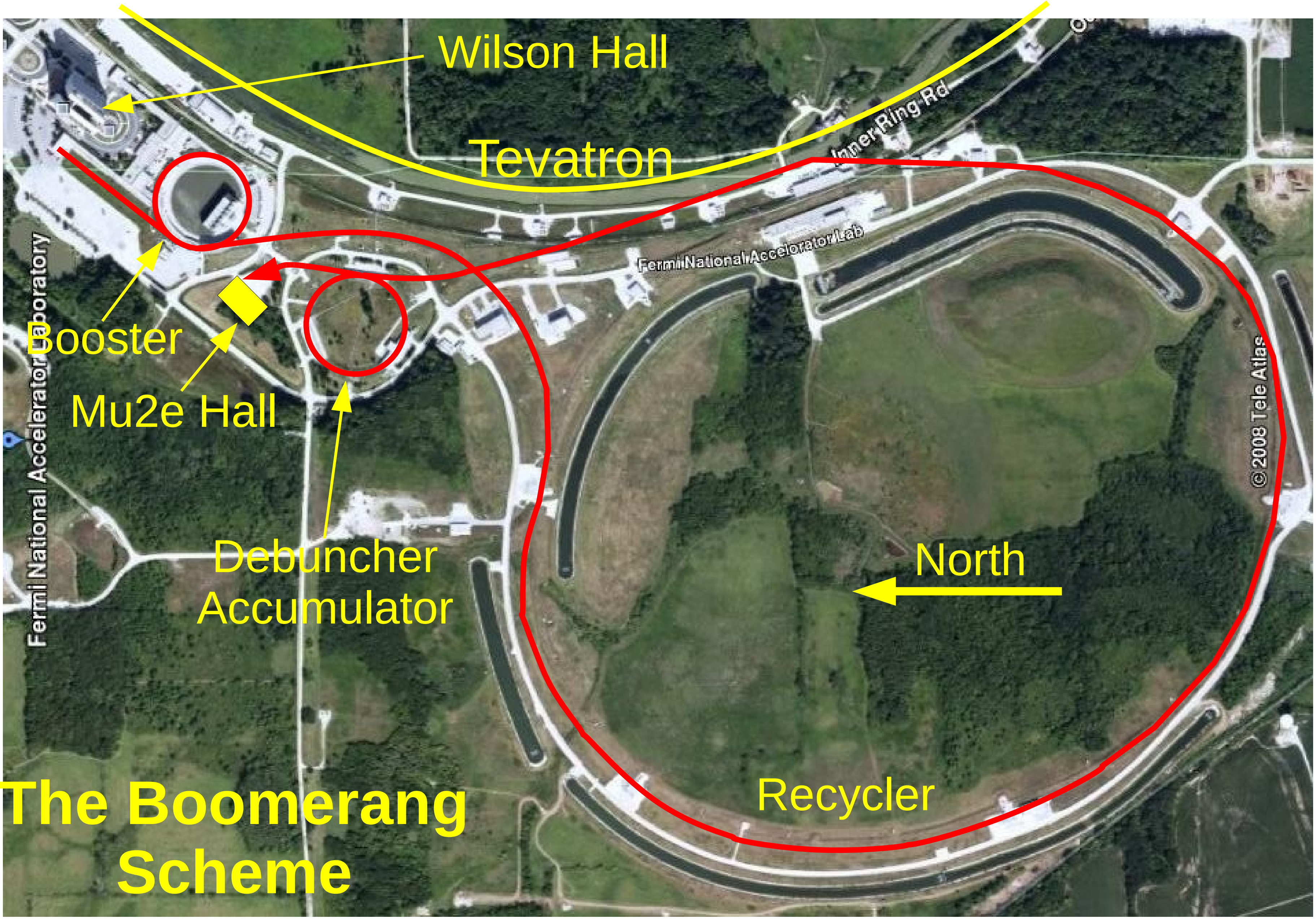

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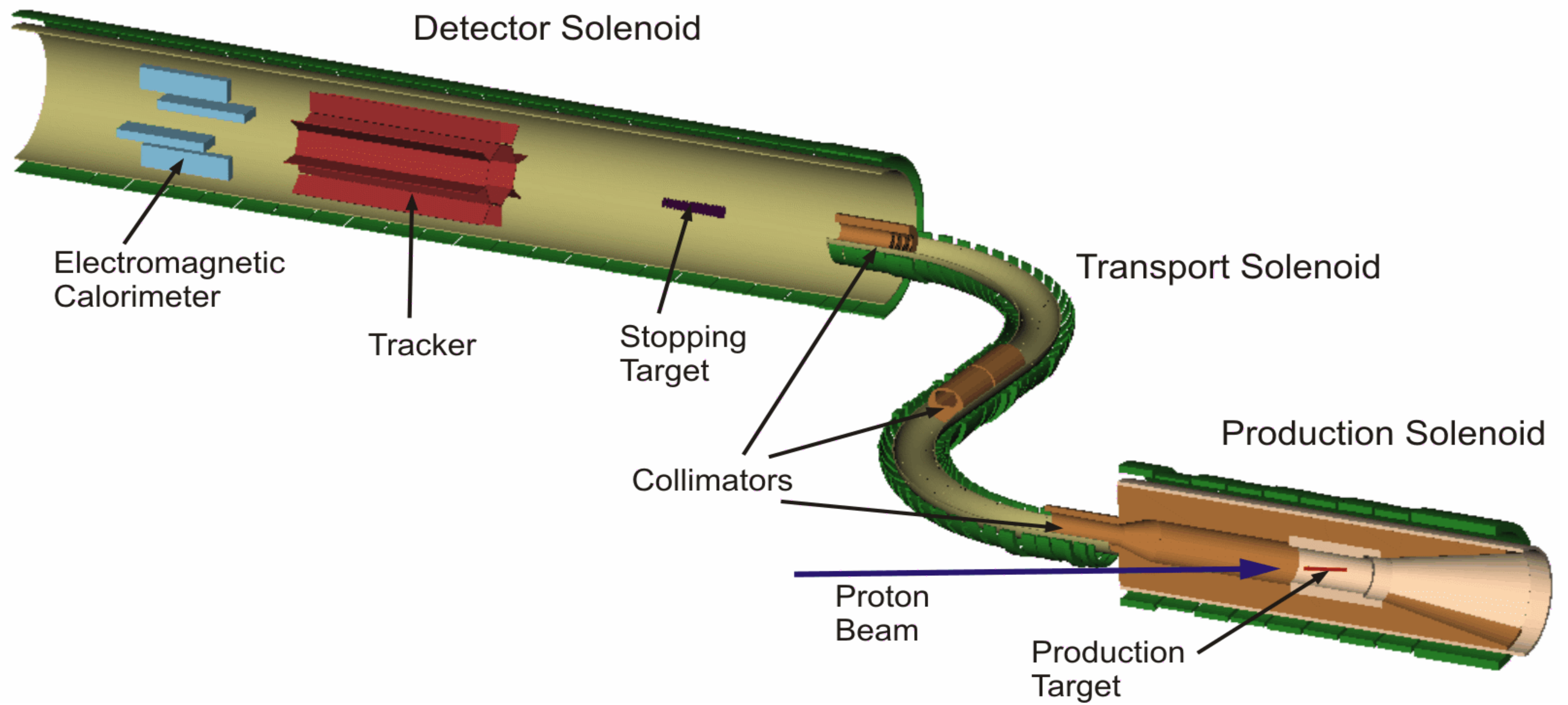

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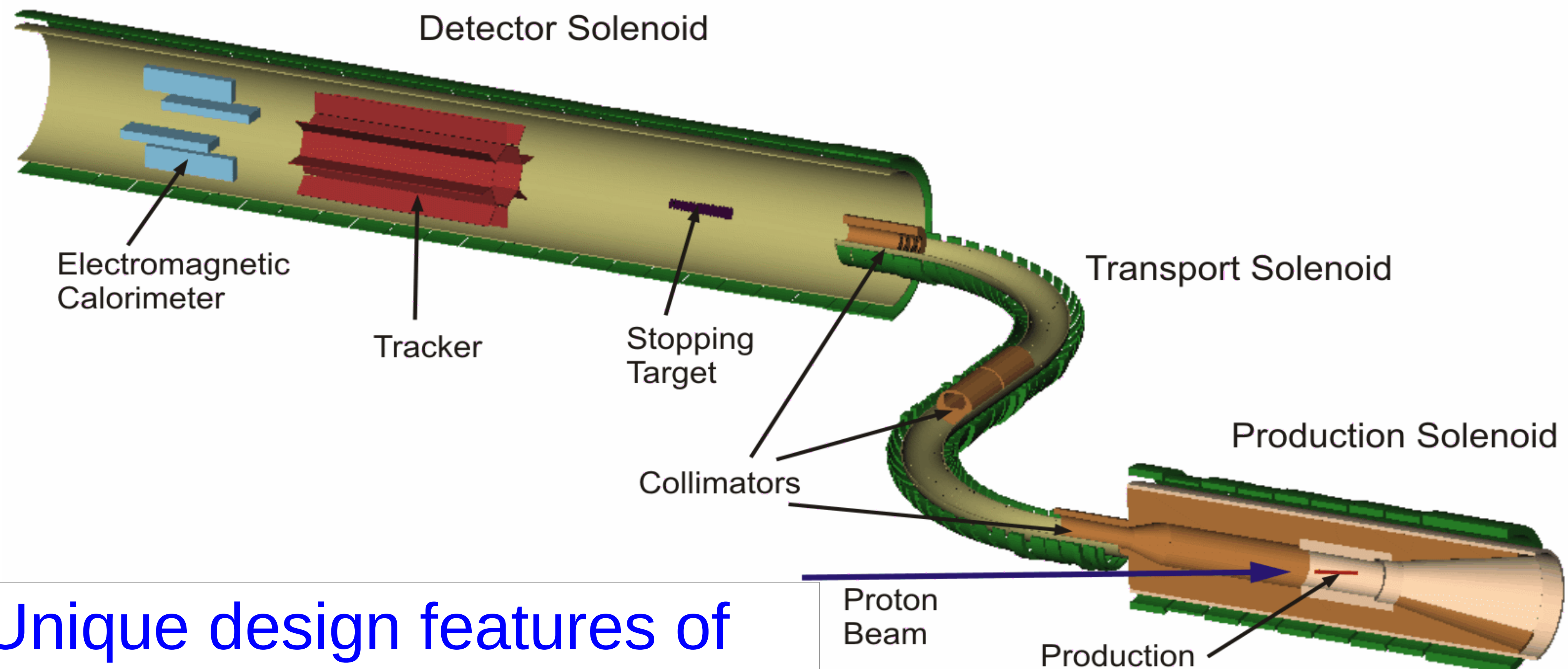
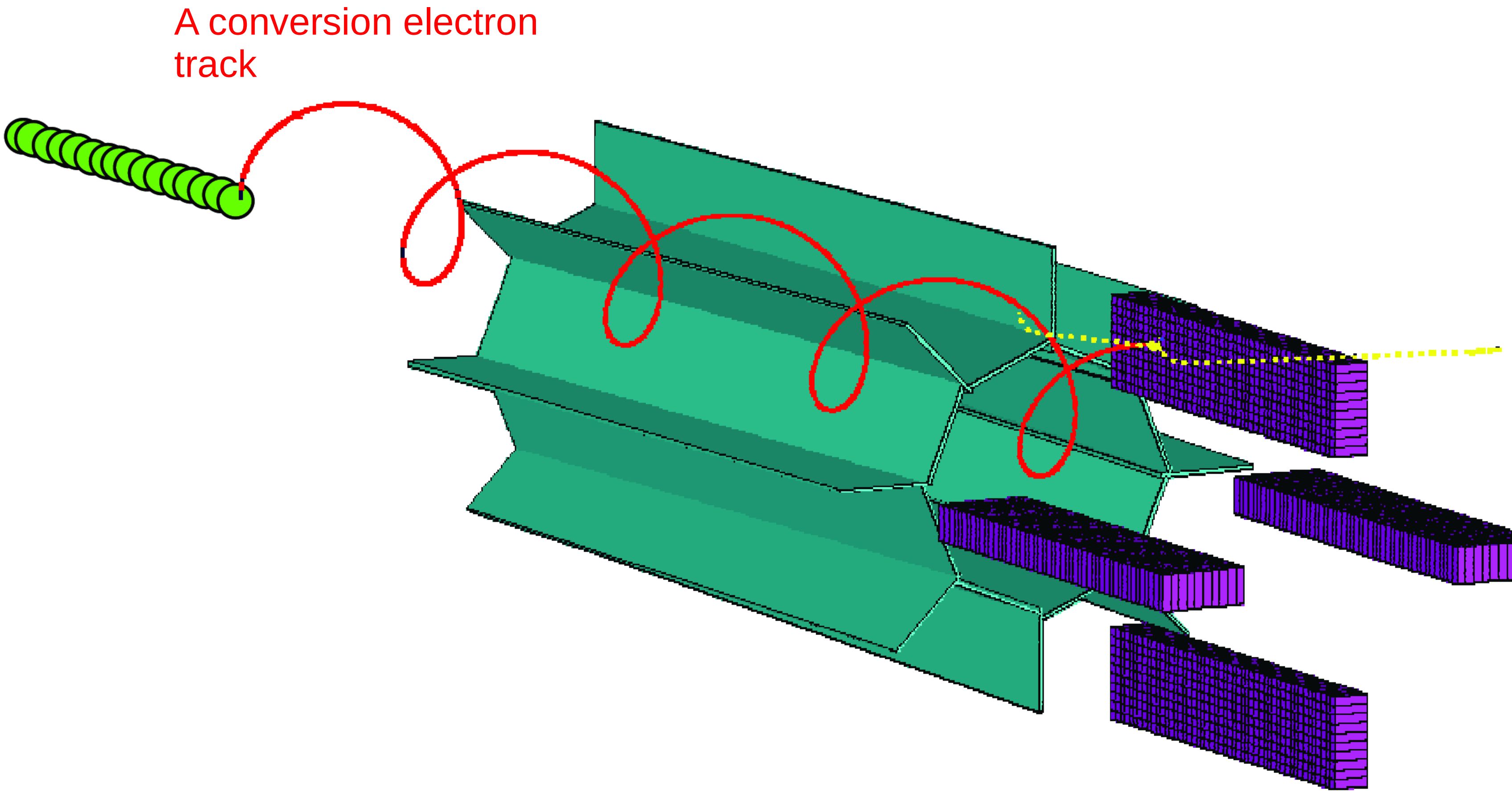


Unique design features of Mu2e:
- Pulsed proton source
- Curved transport solenoid
- Graded detector solenoid fields

The target and detectors



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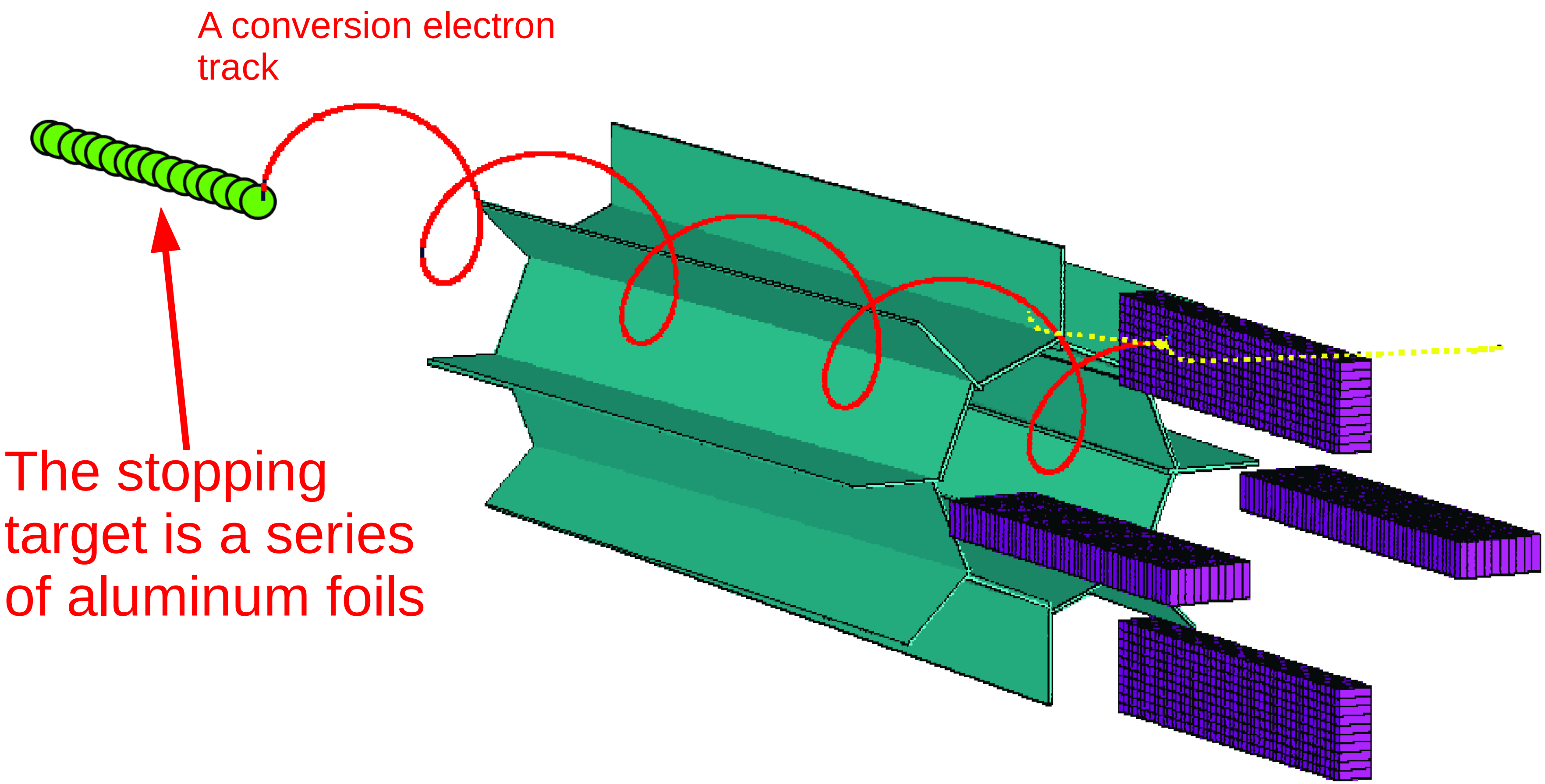

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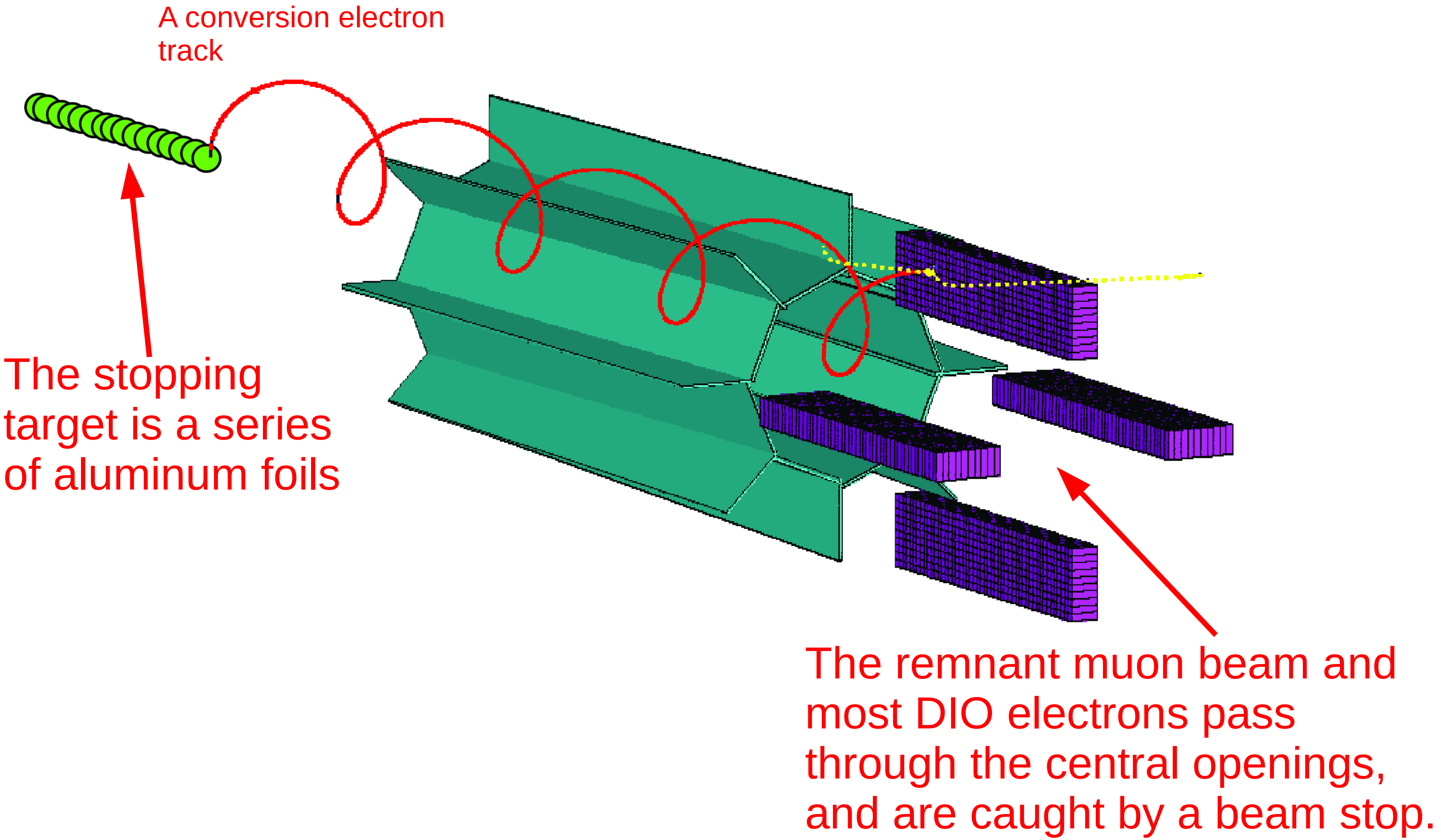

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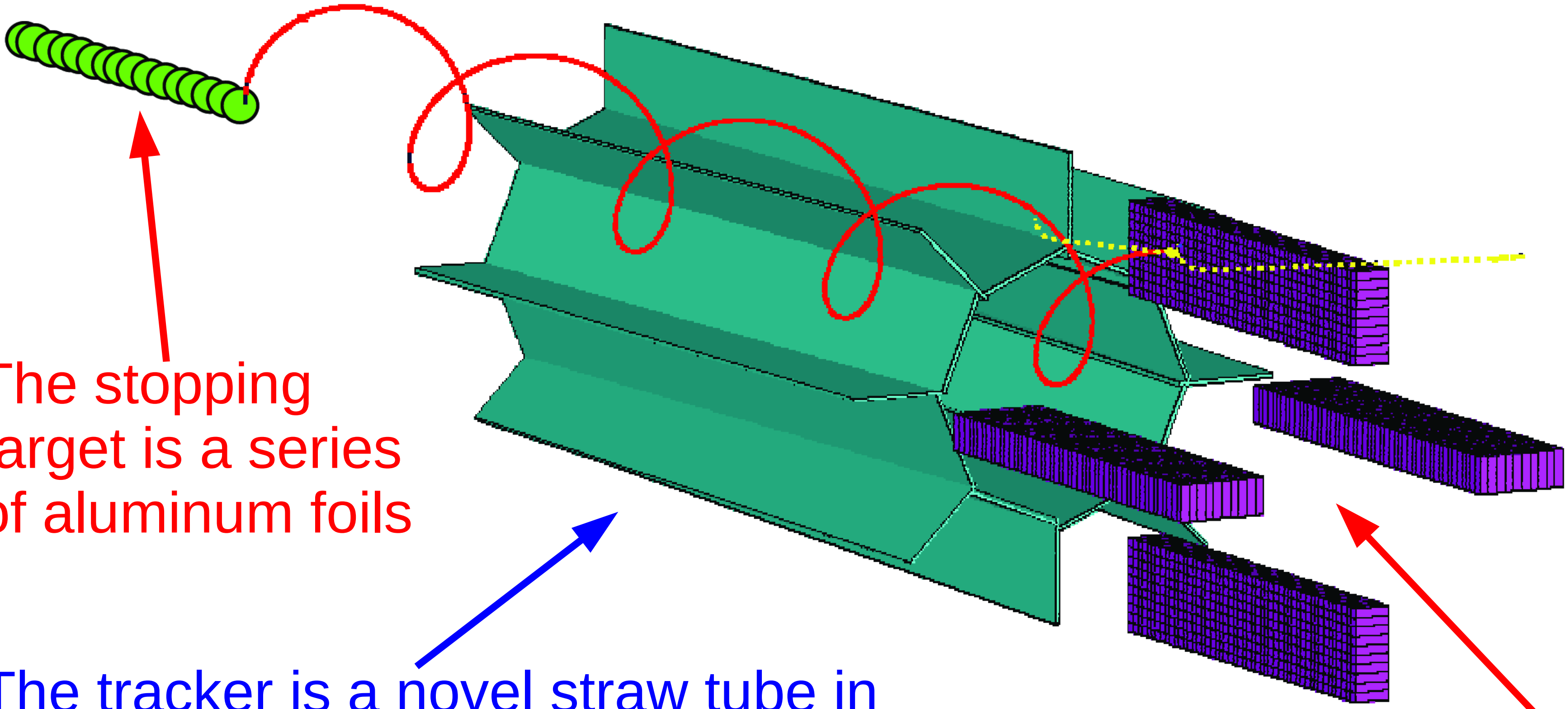

The stopping target is a series of aluminum foils

The tracker is a novel straw tube in vacuum design. A number of baseline designs are under consideration; all would have or order 20000 readout channels.

The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.

The target and detectors

The crystal calorimeter provides direct measures of track position, time, and energy to help protect against catastrophic reconstruction errors.

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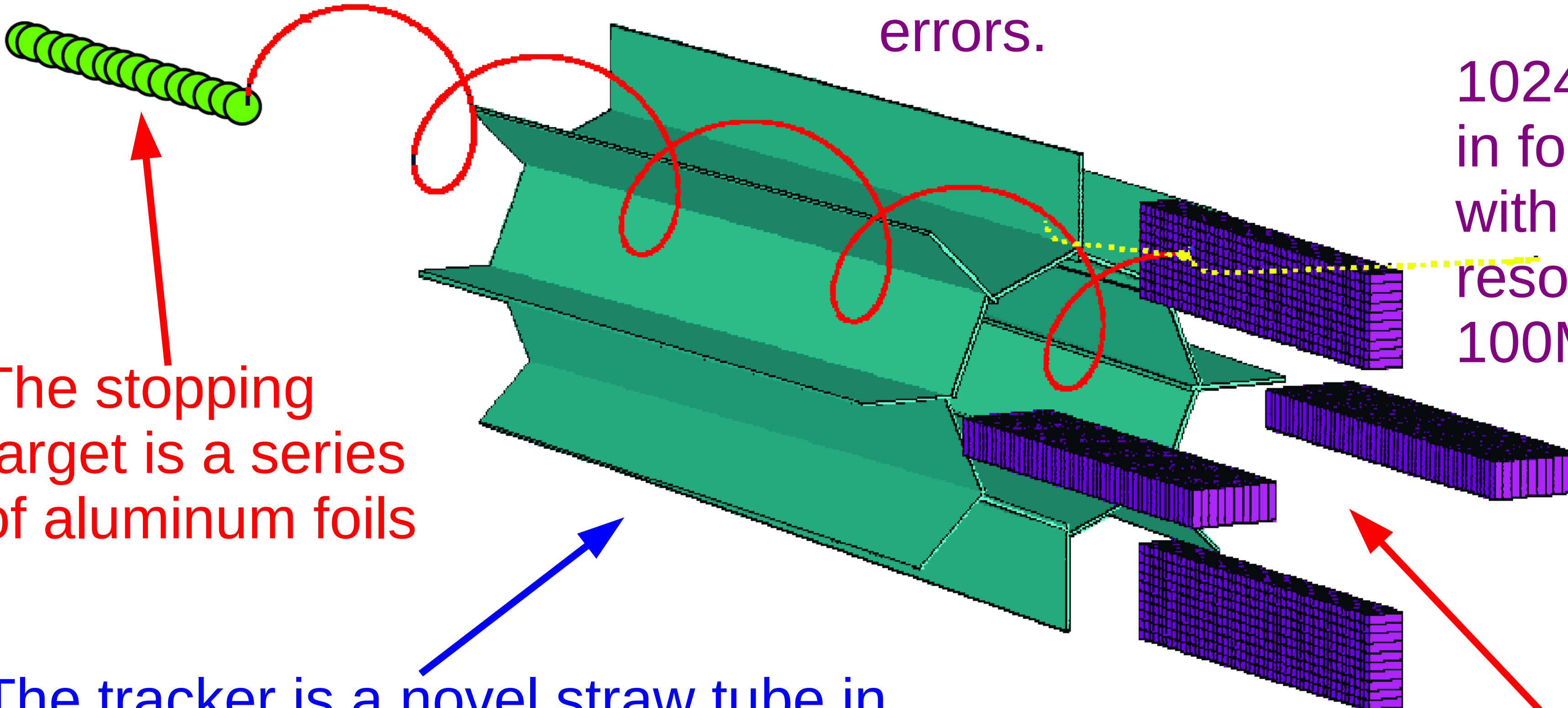

1024 crystals in four vanes with 4MeV resolution at 100MeV

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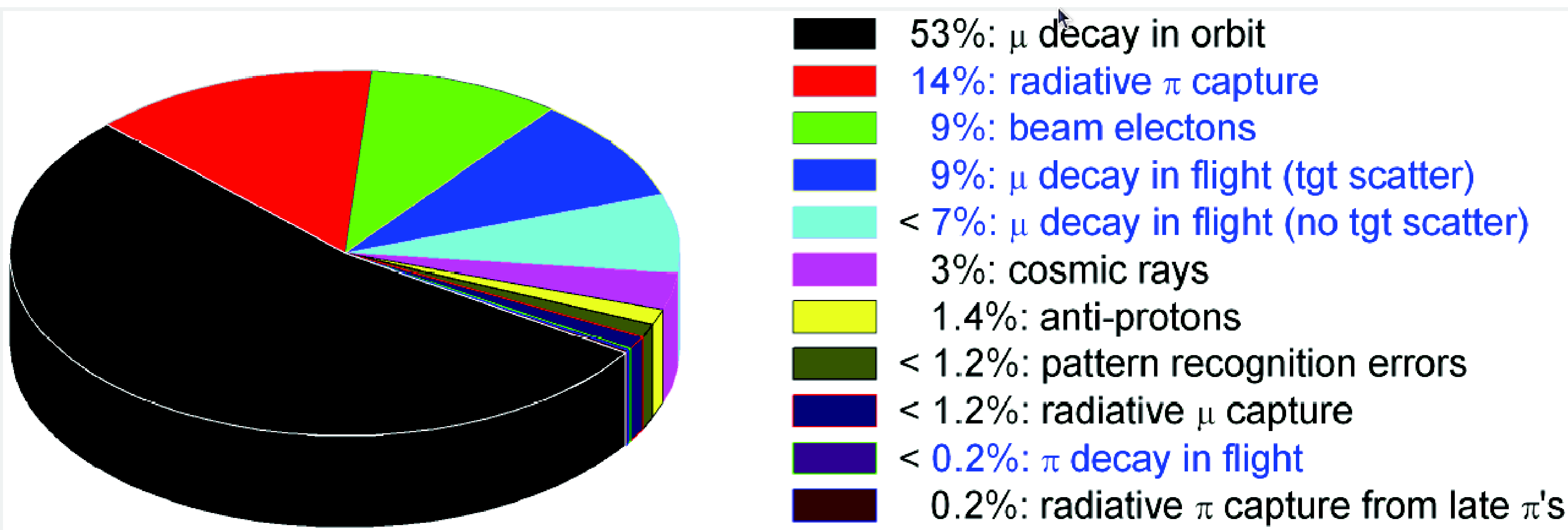
With this design, the background rates are indeed very small!

Background	Events per $2x10^7$s
μ DIO	0.225
Radiative π capture	0.072
μ DIF	0.072
Scattered beam e	0.035
Total	**0.41**



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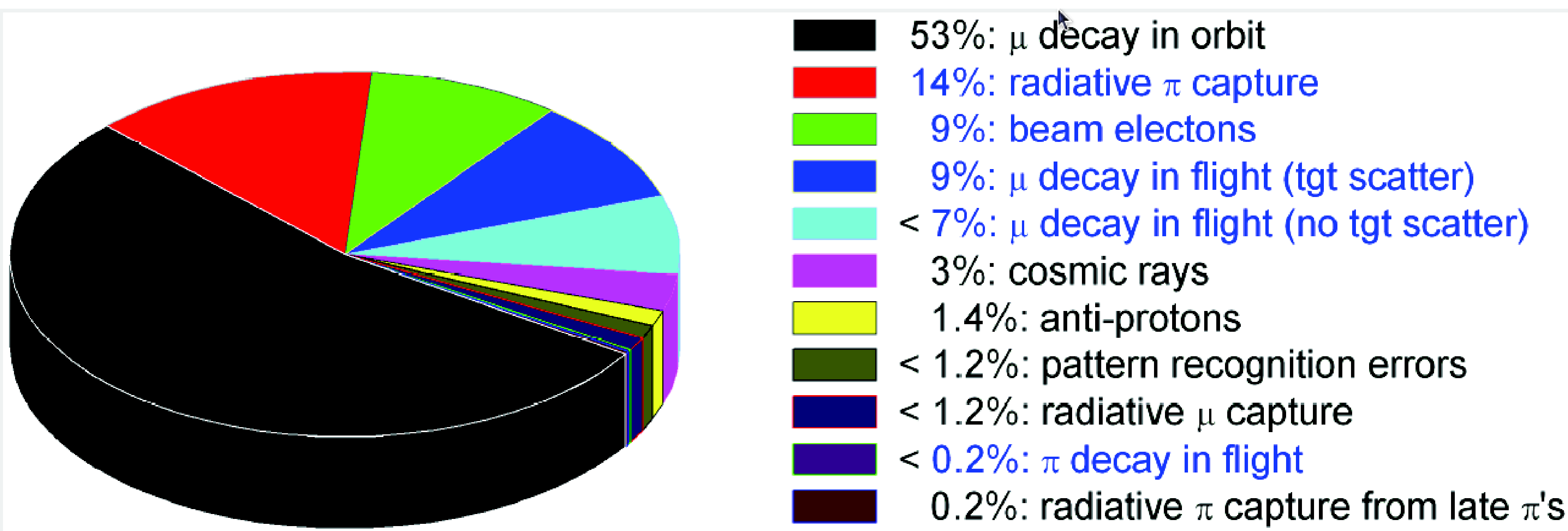

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If $R_{\mu e} = 10^{-15}$, we will see 40 signal events

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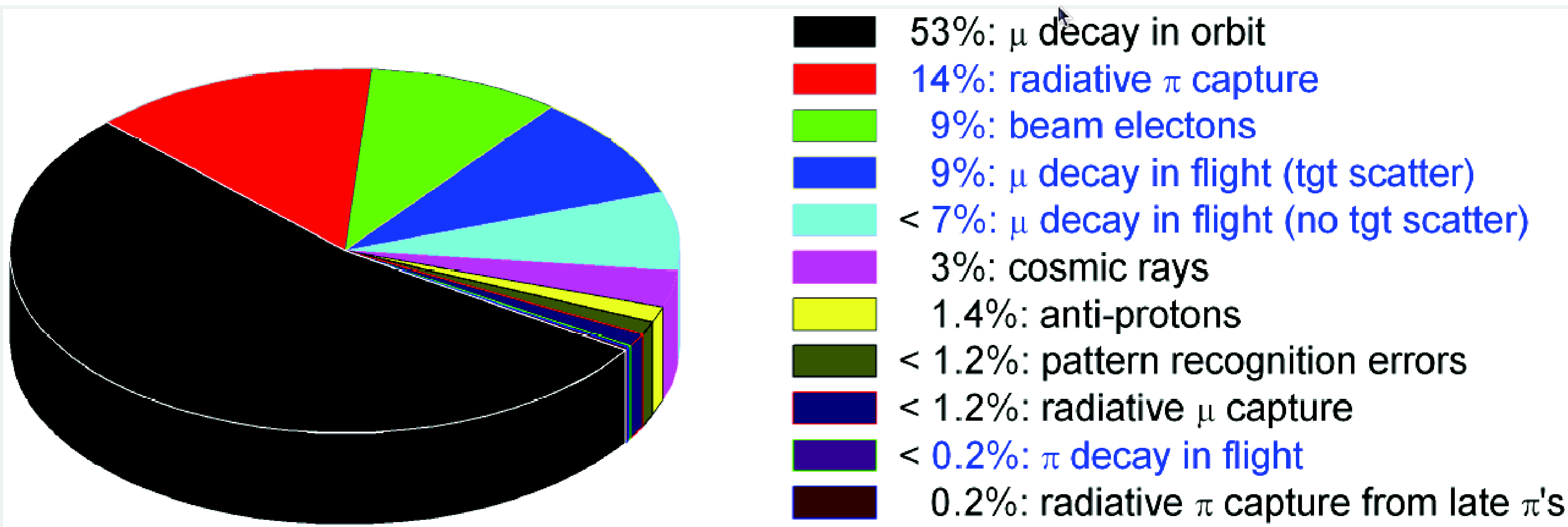
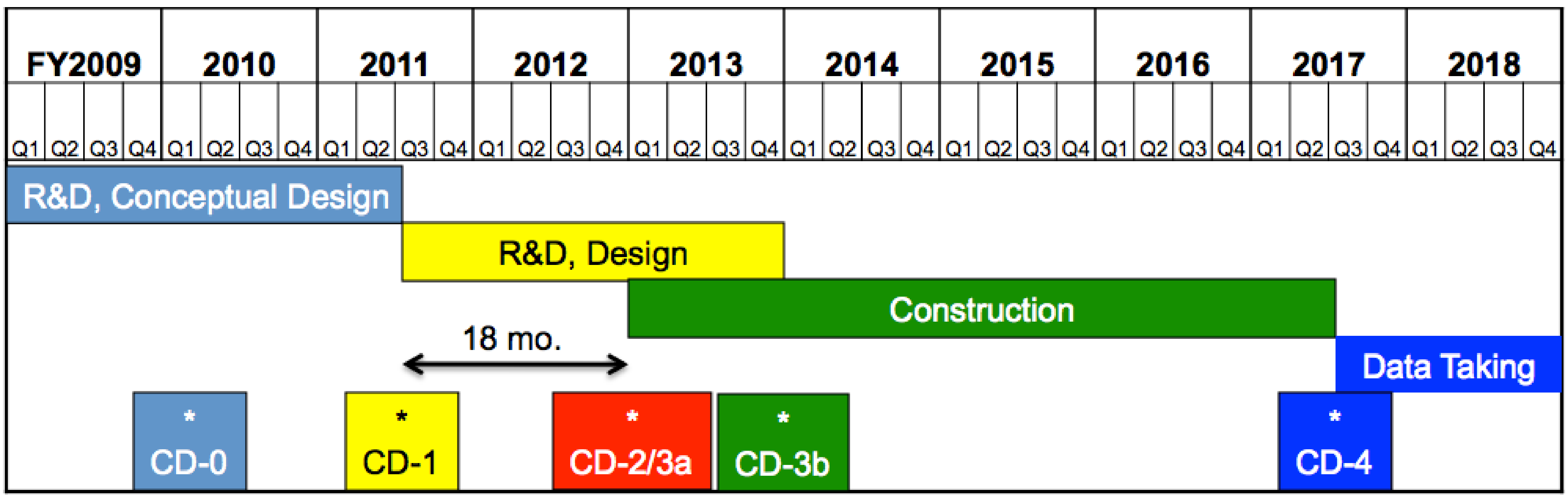


The schedule is technically driven

- We have received both Stage 1 approval and CD-0.
- Magnet design and construction remain the schedule drivers.



Please join us!

- Boston University
- Brookhaven National Laboratory
- City University of New York
- College of William & Mary
- Fermi National Accelerator Laboratory
- Idaho State University
- Instituto Nazionale di Fisica Nucleare, Lecce
- Instituto Nazionale di Fisica Nucleare, Pisa
- Institute for Nuclear Research, Moscow
- Joint Institute for Nuclear Research, Dubna
- Laboratori Nazionali di Frascati
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Muons Inc.
- Northwestern University
- Rice University
- Syracuse University
- University of California, Berkeley
- University of California, Irvine
- University of Houston
- University of Illinois
- University of Massachusetts, Amherst
- University of Virginia
- University of Washington

Contact:
Bob Bernstein, *rhbob@fnal.gov*, or
Jim Miller, *miller@bu.edu*.

We normalize the conversions with the captures

$$R_{\mu e} = \frac{\Gamma\left(\mu^- A \to e^- A\right)}{\Gamma\left(\mu^- A \to \nu_\mu A'\right)}$$

$$= \frac{N_{\mu e}/\epsilon_{\mu e}}{N_{\text{stops}}/\epsilon_{\text{stops}}\ \left(\Gamma_{\mu\nu}/\Gamma_{\text{total}}\right)}$$

Events in signal window → $N_{\mu e}$

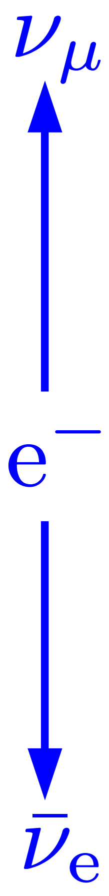
Acceptance for signal events → $\epsilon_{\mu e}$

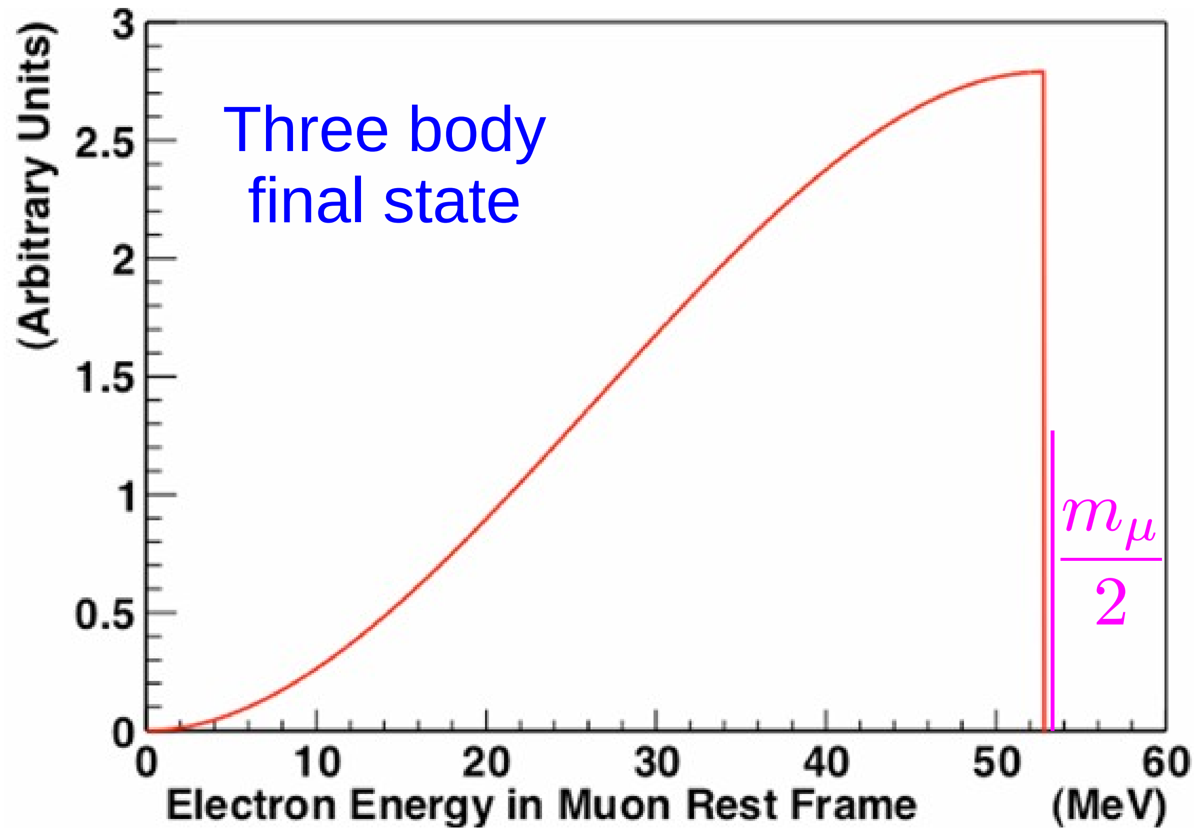
Directly measured via cascade X-Rays → N_{stops}

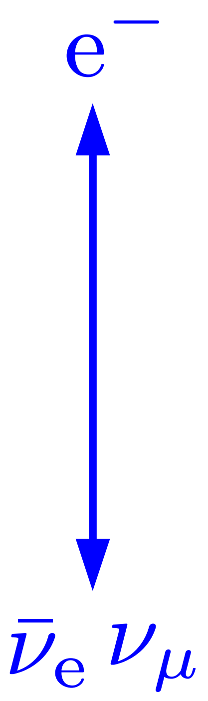
Well known nuclear capture ratio → $\Gamma_{\mu\nu}/\Gamma_{\text{total}}$

Muon Decay-in-Orbit

First, consider the free decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$



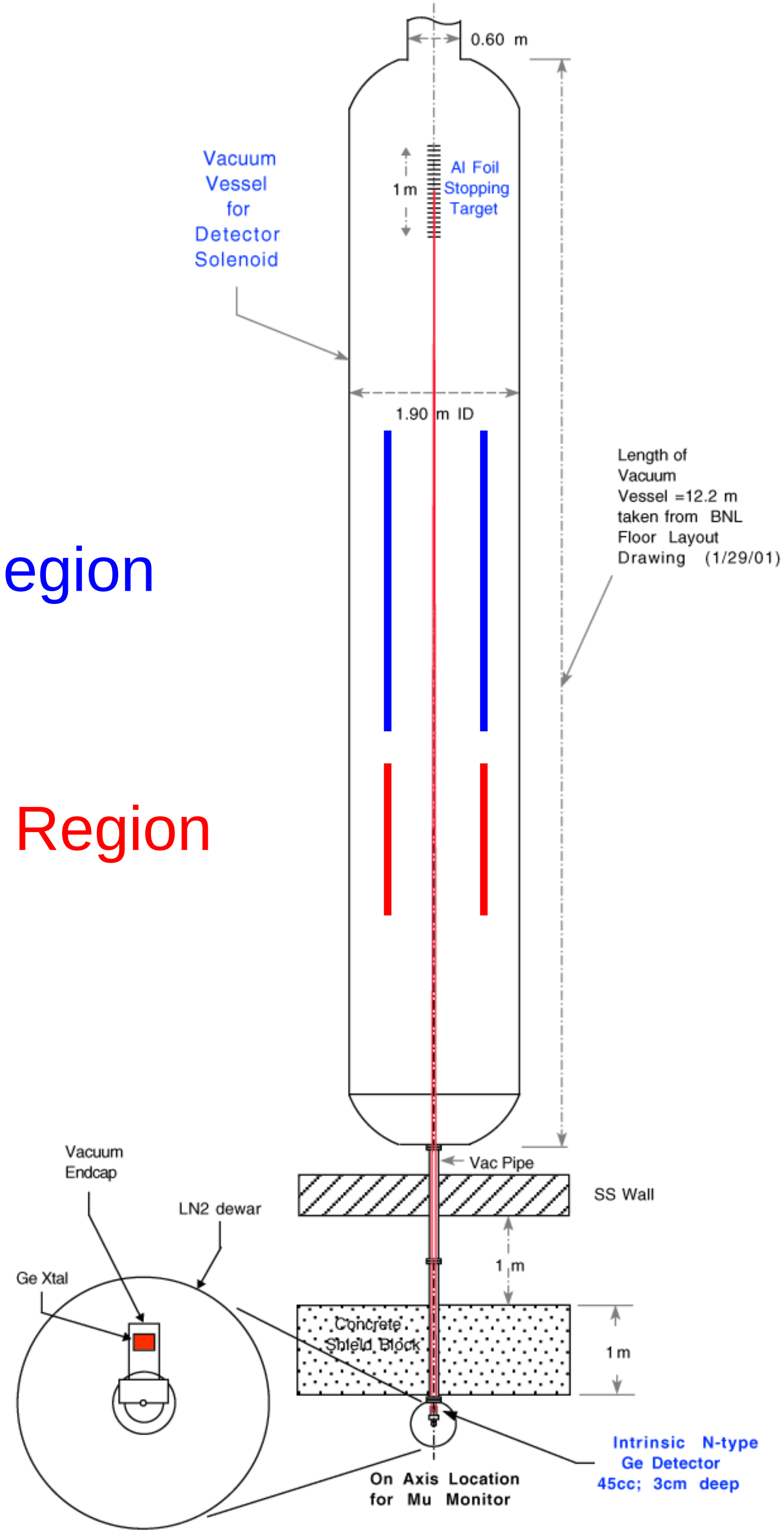




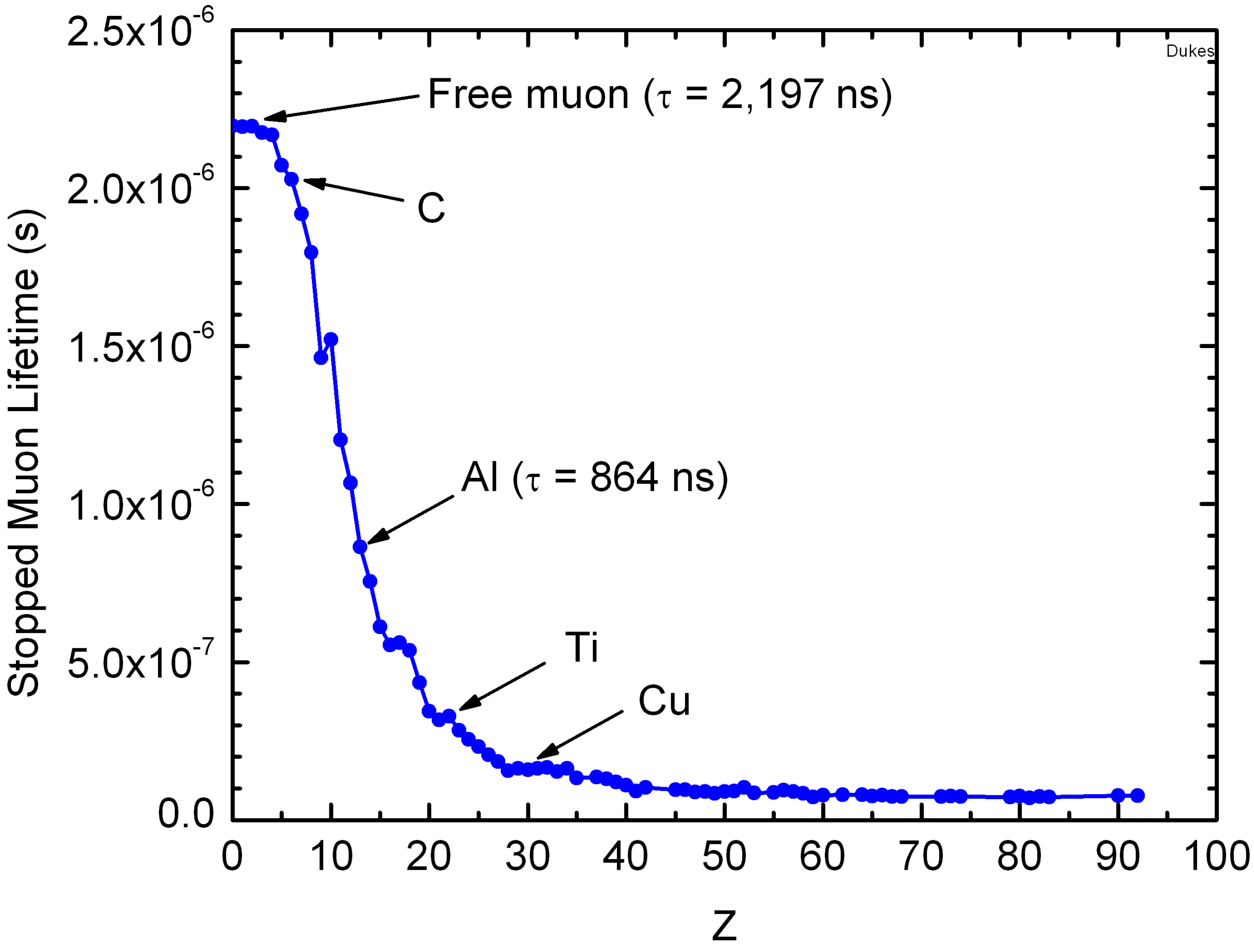
Monitoring the muon stopping rate

Tracker Region

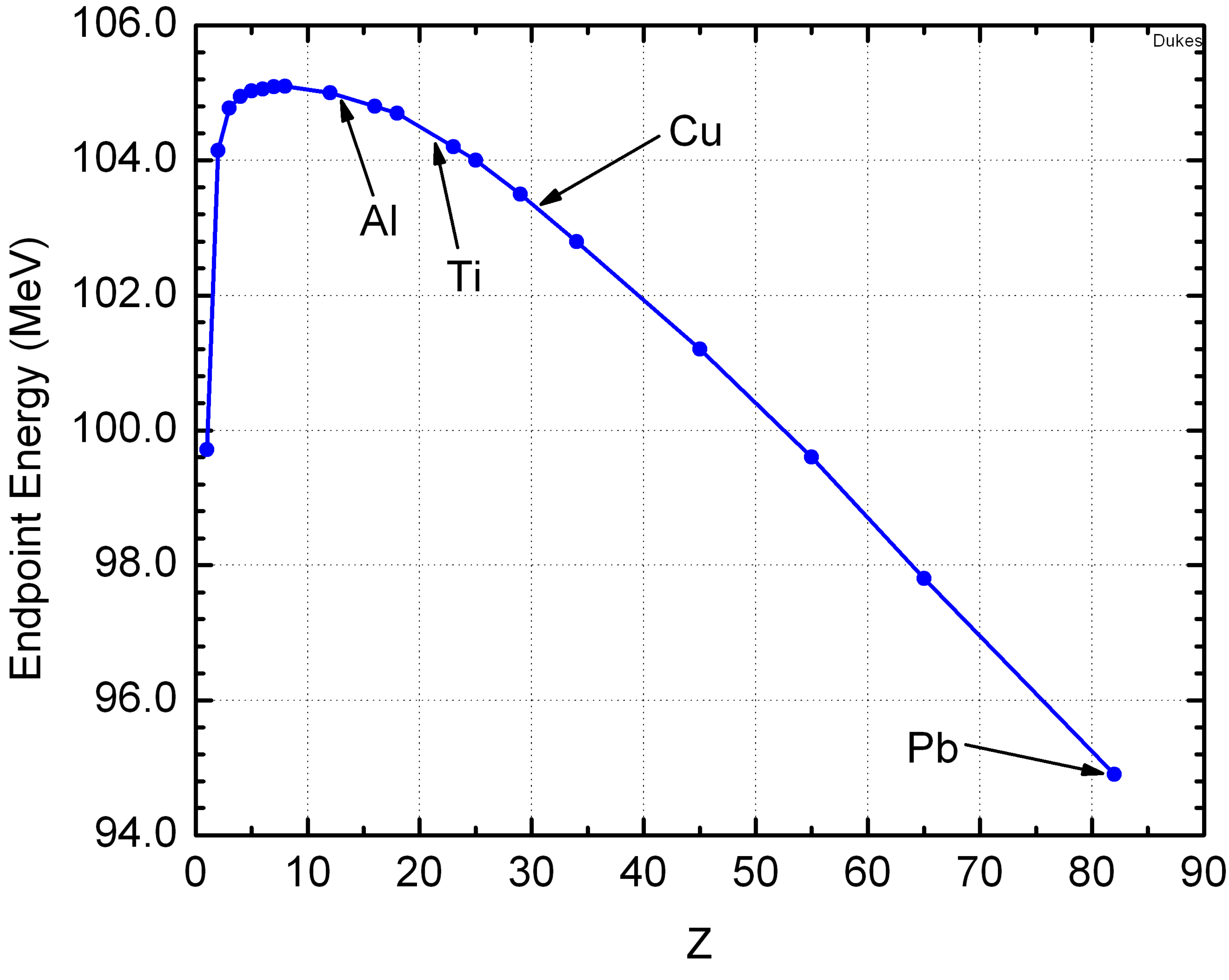
Calorimeter Region



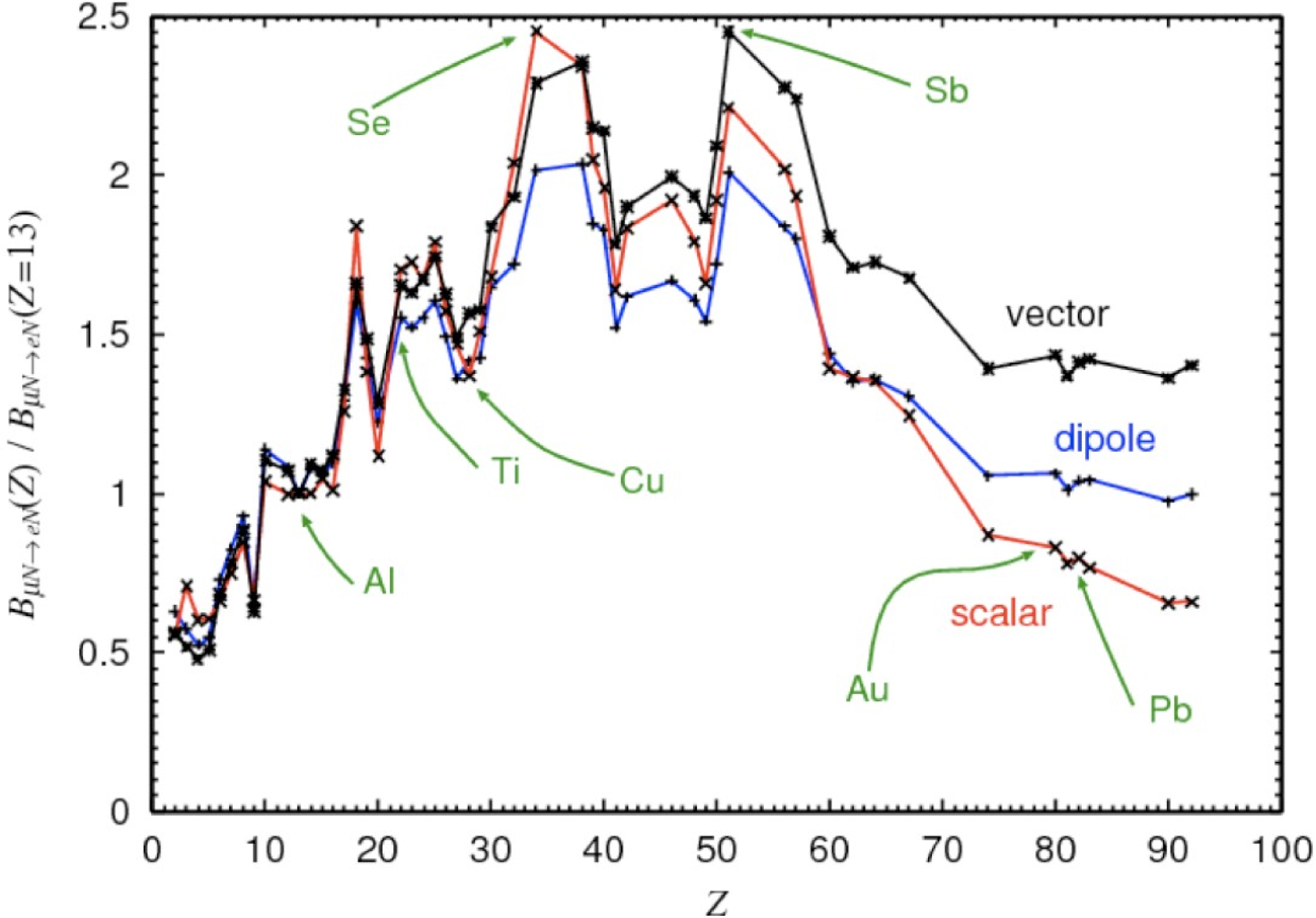
The choice of Al is well matched to the FNAL beam time structure



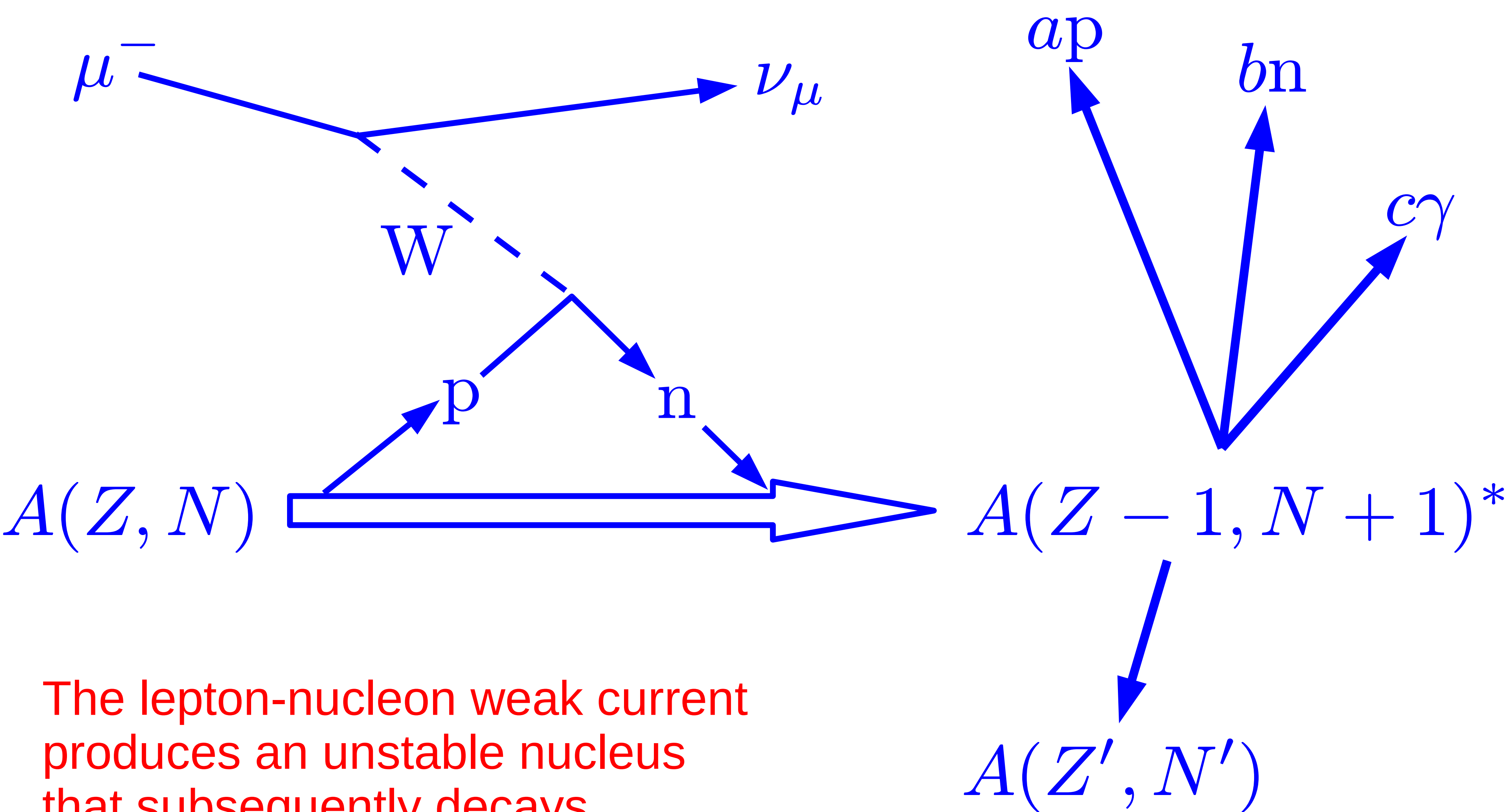
The endpoint energy is material dependent



Different materials are sensitive to different operators



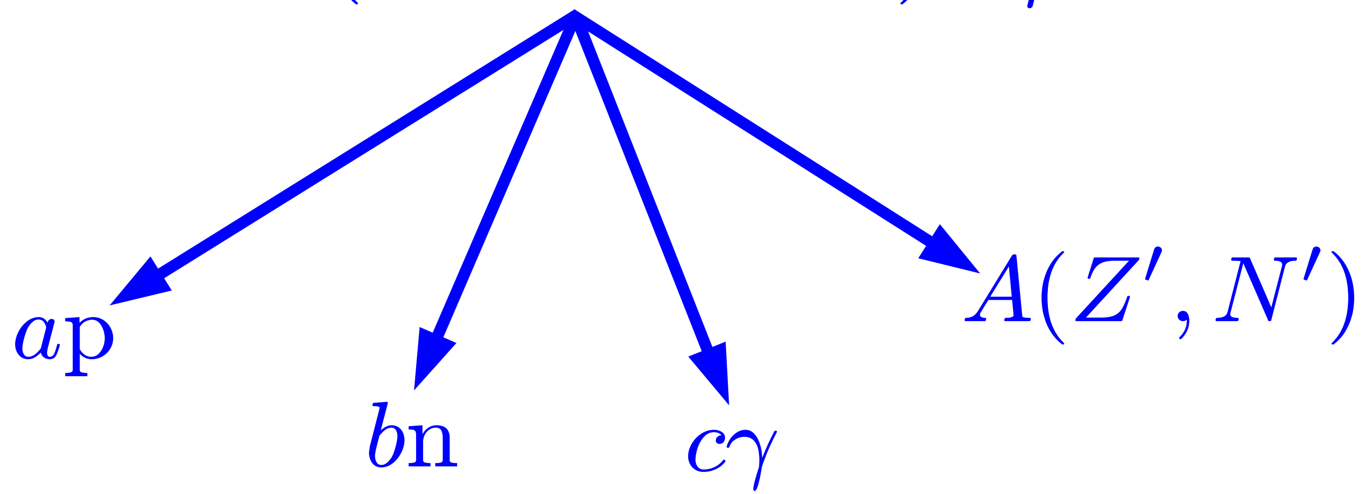
Nuclear capture is both normalization and a source of inefficiency due to extra hits



The lepton-nucleon weak current produces an unstable nucleus that subsequently decays

Nuclear capture is both normalization and a source of inefficiency due to extra hits

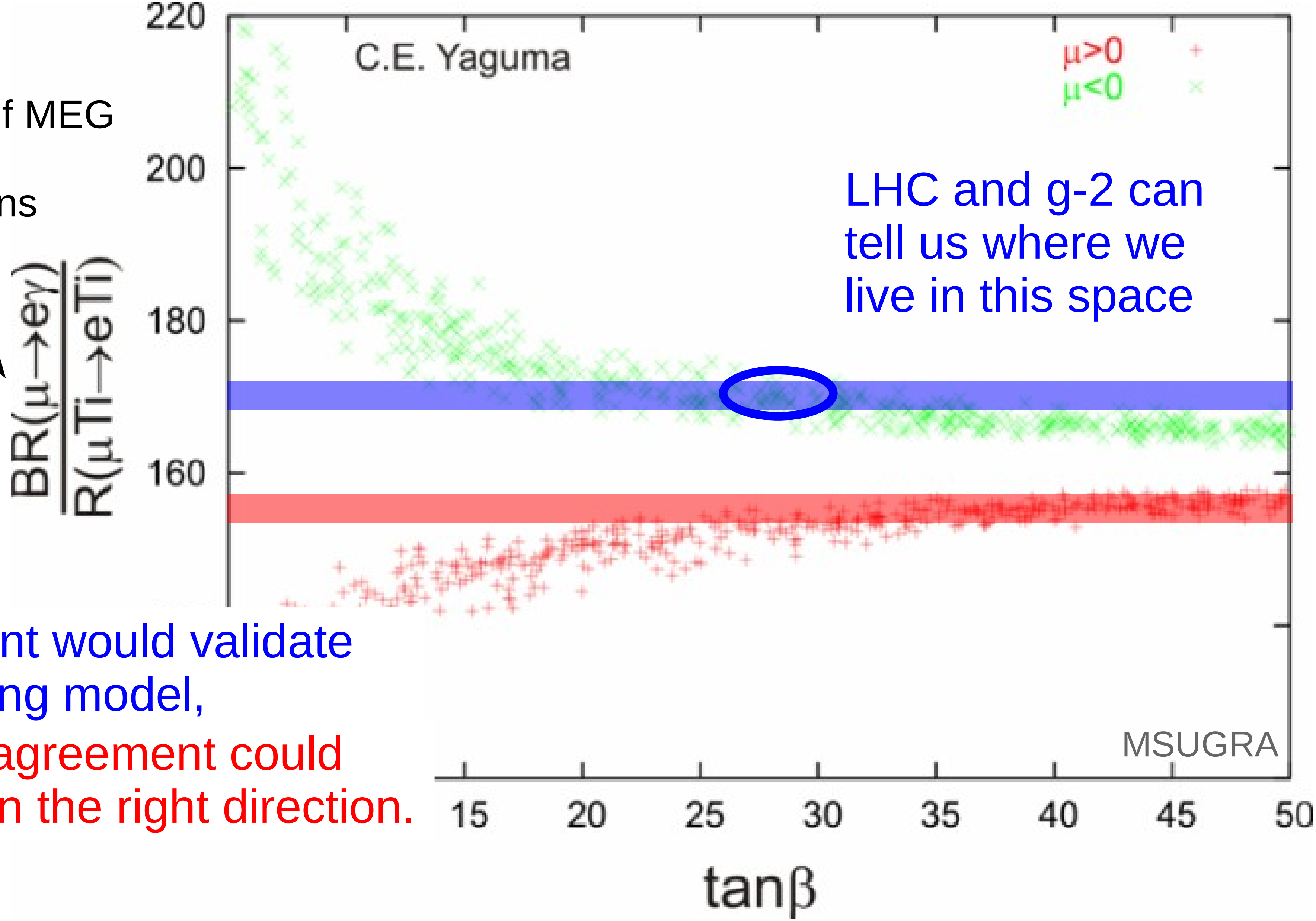
$$A(Z,N)\mu^- \rightarrow A(Z-1,N+1)^*\nu_\mu$$



For an ^{27}Al target, the average capture results in 0.1p, 2n, and 2γ. These result in additional hits in the detectors, potentially leading to inefficiency and pattern recognition errors.

Conversion is just one complementary piece of the flavor puzzle

The ratio of MEG to Mu2e observations



LHC and g-2 can tell us where we live in this space

Agreement would validate any leading model,

while disagreement could point us in the right direction.

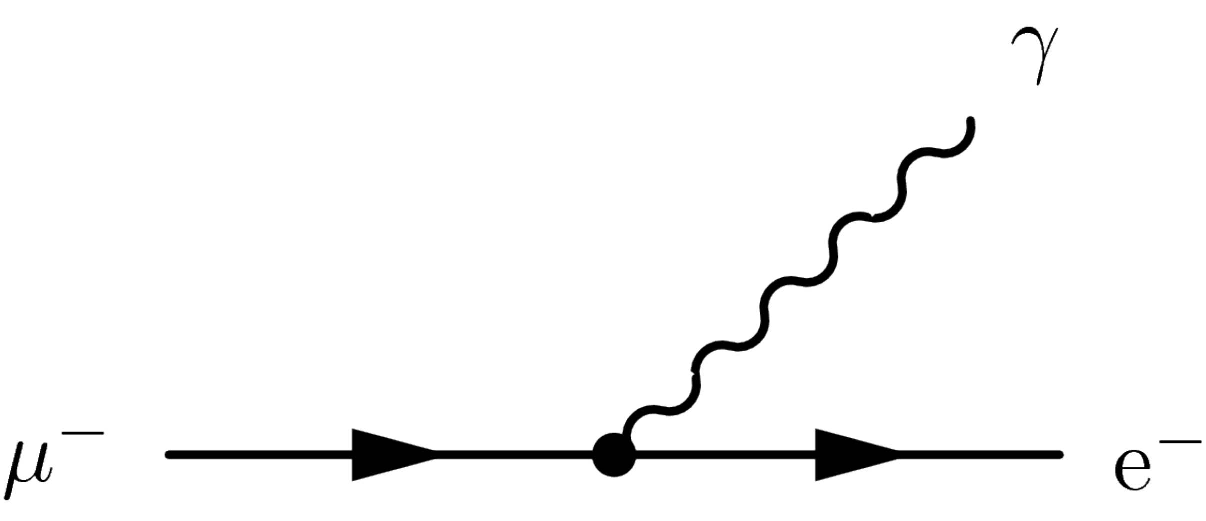
Different cLFV processes are driven by different operators

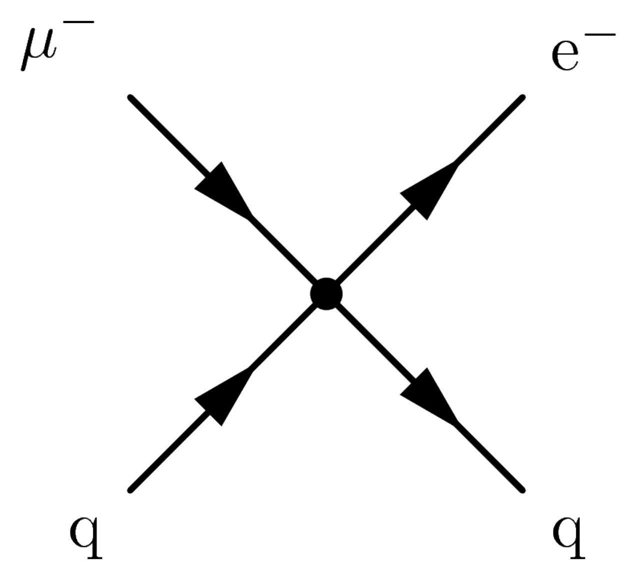
Hence, measurements of the different processes tell us about the underlying physics

$$\mathcal{L}_{\mathrm{cLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\alpha\beta} \mathrm{e}_L F^{\alpha\beta} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\alpha \mathrm{e}_L \left(\bar{\mathrm{u}}_L \gamma^\alpha \mathrm{u}_L + \bar{\mathrm{d}}_L \gamma^\alpha \mathrm{d}_L\right)$$

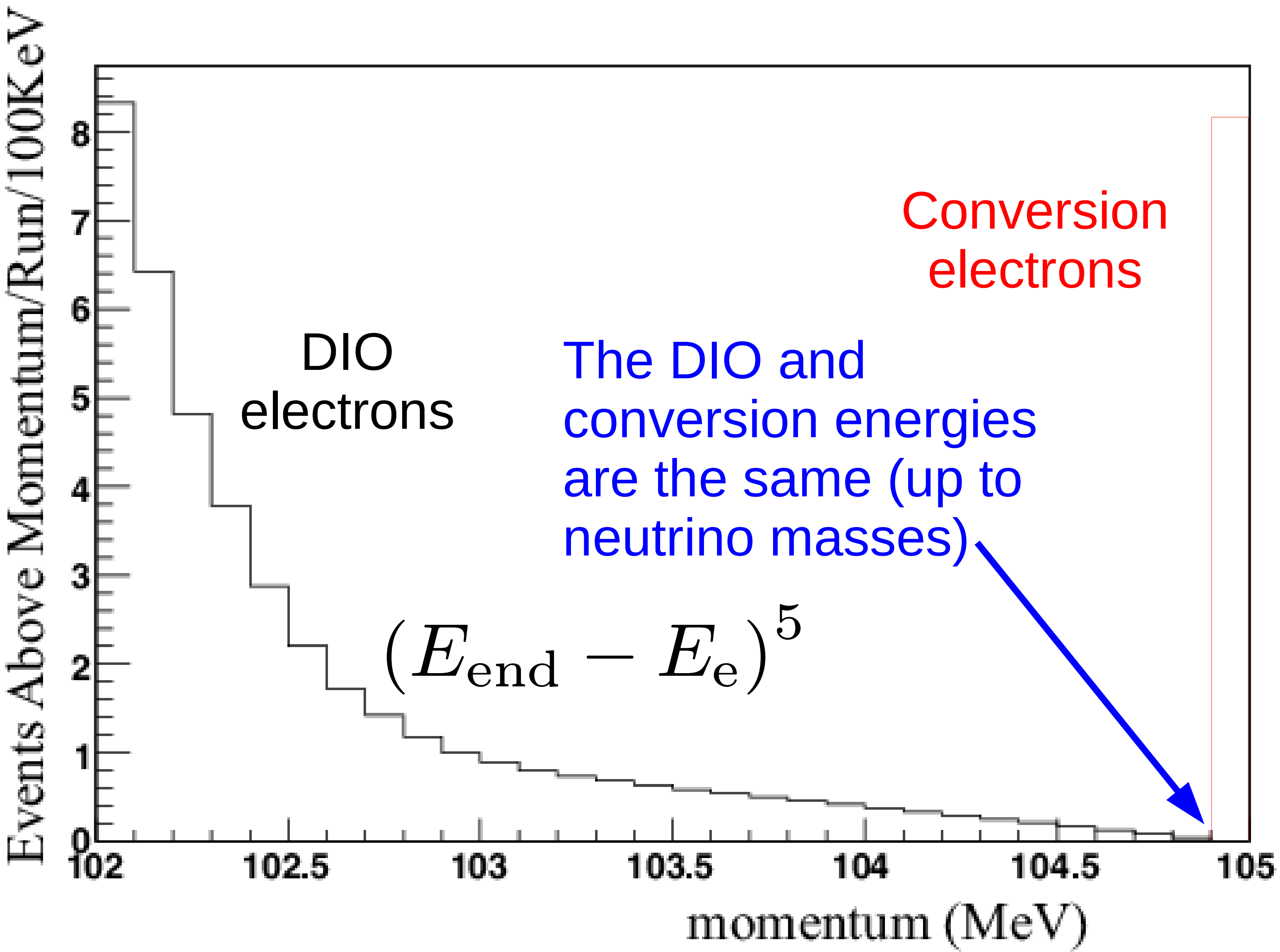
Chirality violating dipole interaction

Chirality preserving contact interaction





But the DIO endpoint is the conversion energy



In the Project X era ...

... beam power will increase 10-100 fold. Mu2e naturally extends into this era, regardless of the first generation results.

With no signal

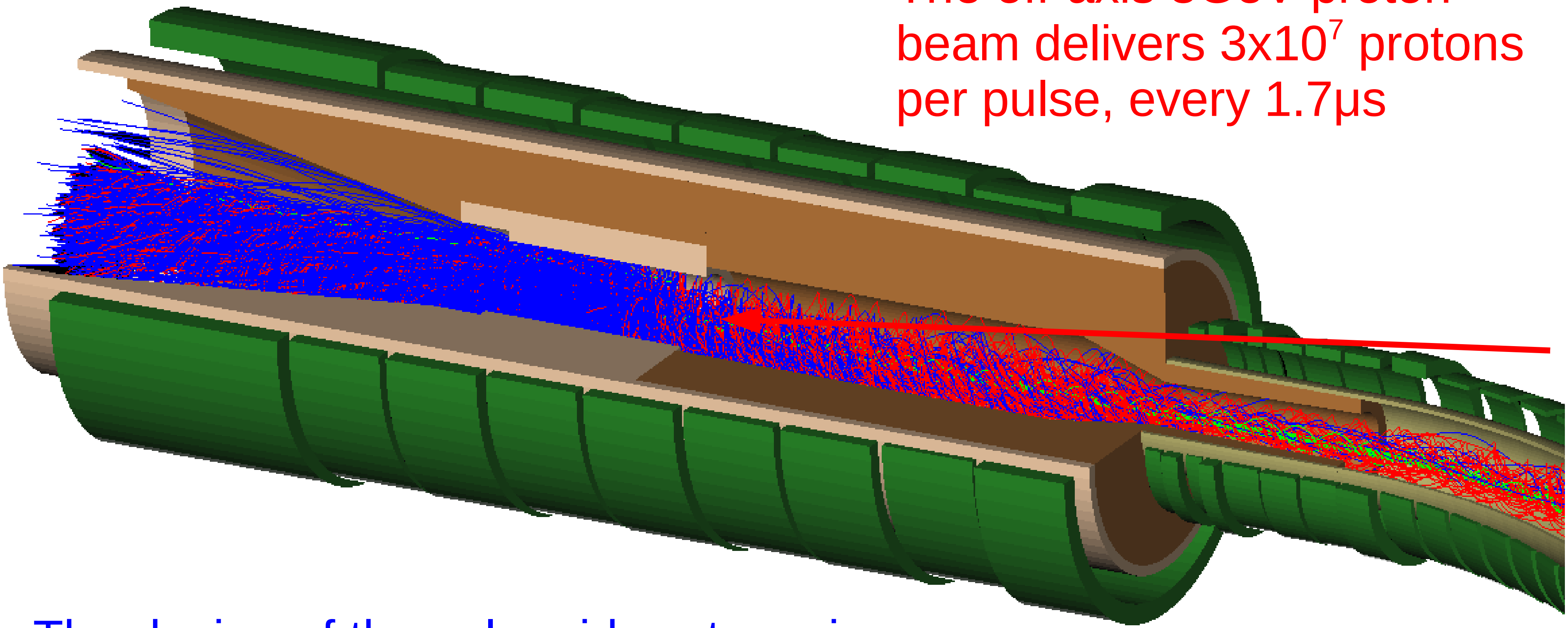
- All backgrounds must be further suppressed to reach $R_{\mu e}$ of 10^{-18}
- All detector and transport systems will need upgrades to handle the higher rates

If we do see a signal

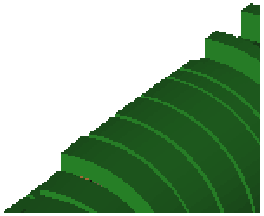
- Change target material to determine structure of new physics amplitudes
- All detector and transport systems will need upgrades to handle the higher rates

Muon production solenoid

The off-axis 8GeV proton beam delivers 3x10^{7} protons per pulse, every 1.7μs

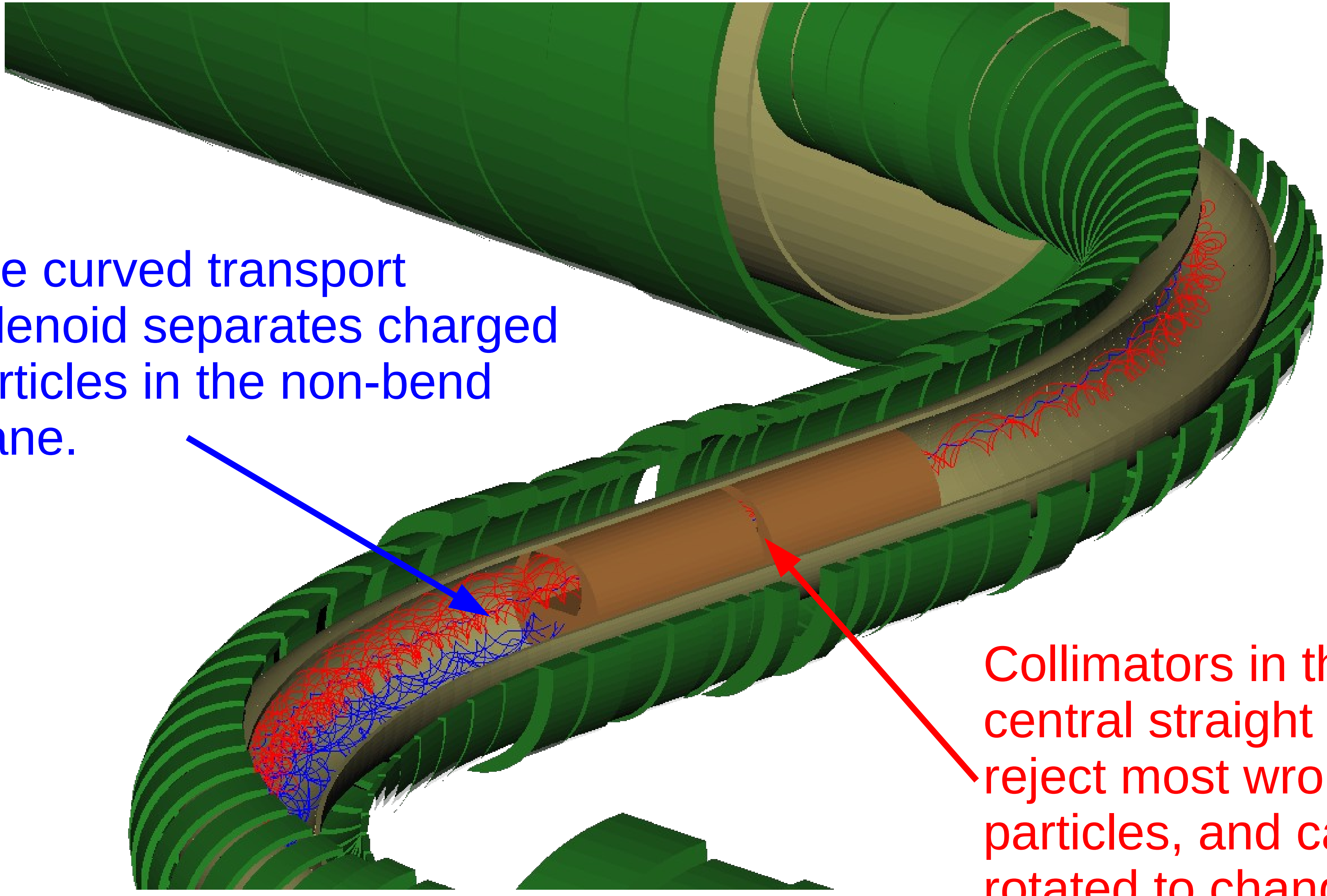


The design of the solenoid systems is a collaborative effort among TD, AD, and Physicists: “It's not just a big gizmo for TD to build ... we need University people to get involved!”



Transport solenoid

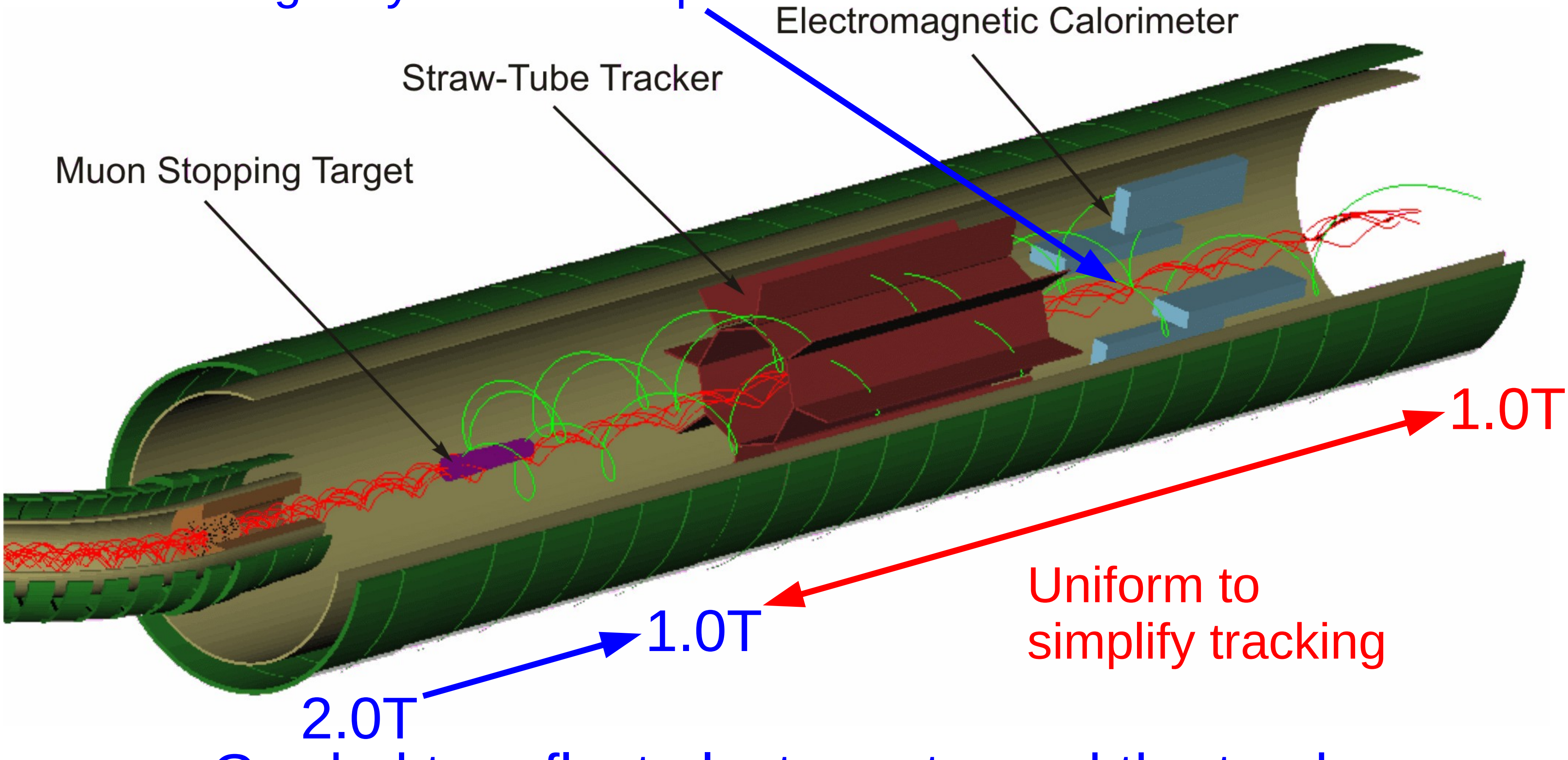
The curved transport solenoid separates charged particles in the non-bend plane.



Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

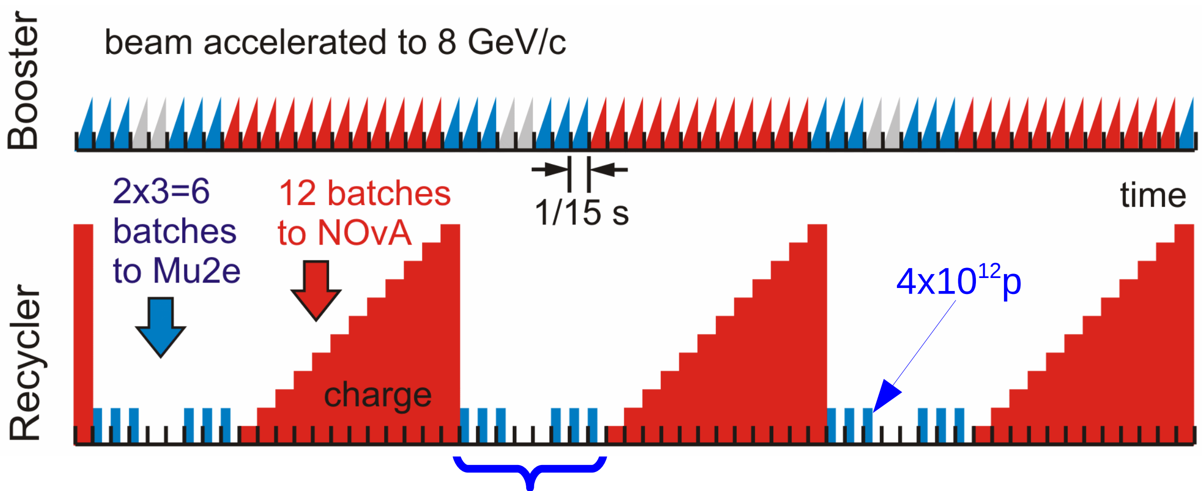
The detector solenoid and stopping target

The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.



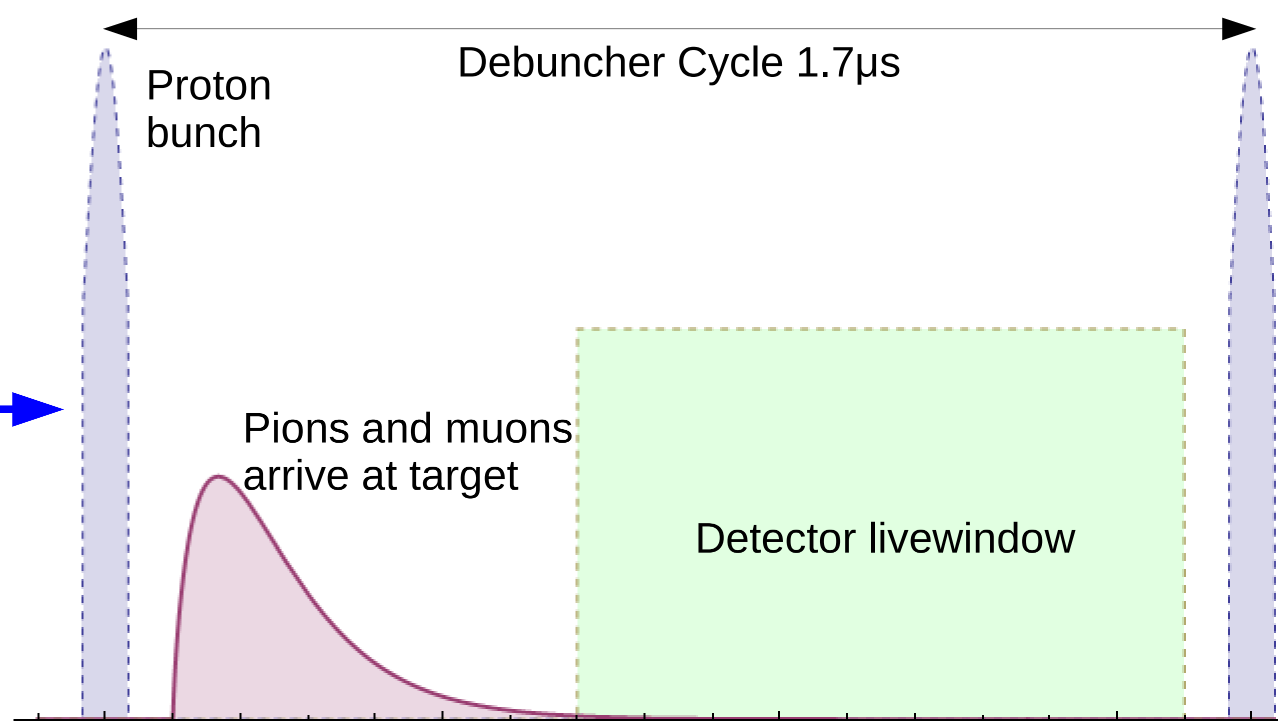
Graded to reflect electrons toward the tracker

We will utilize *unused* Booster batches during Nova running

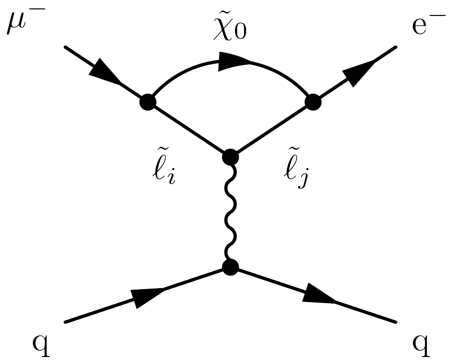


Mu2e running does not impact the neutrino program!

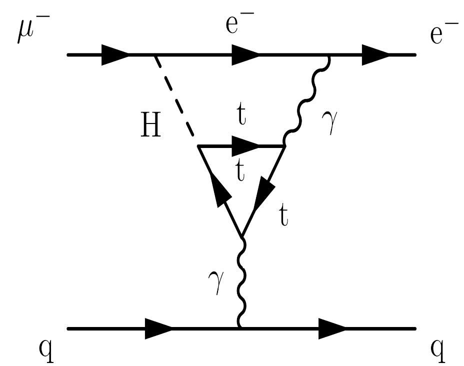
These batches are stacked and bunched in the accumulator, then transferred to the debuncher for slow extraction to Mu2e



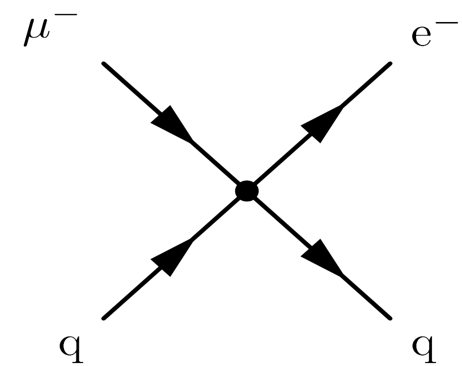
Muon conversion arises in many new physics scenarios



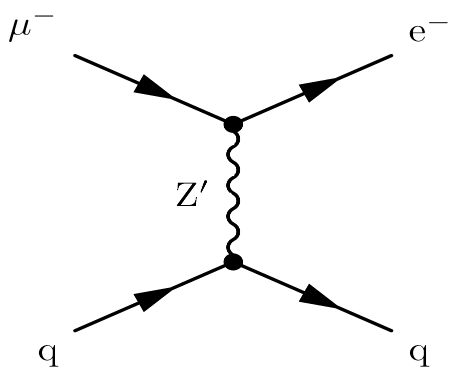
SUSY



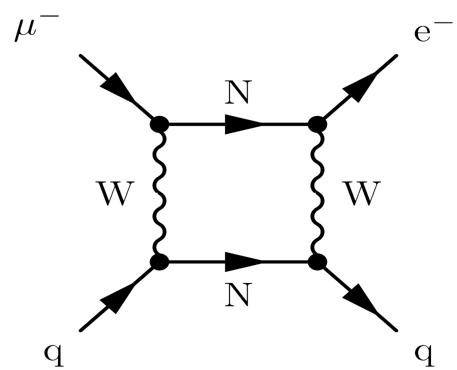
Second Higgs Doublet



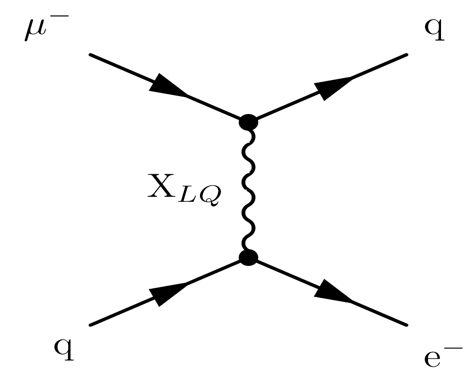
Compositeness



Heavy Gauge Bosons



Heavy Neutrinos

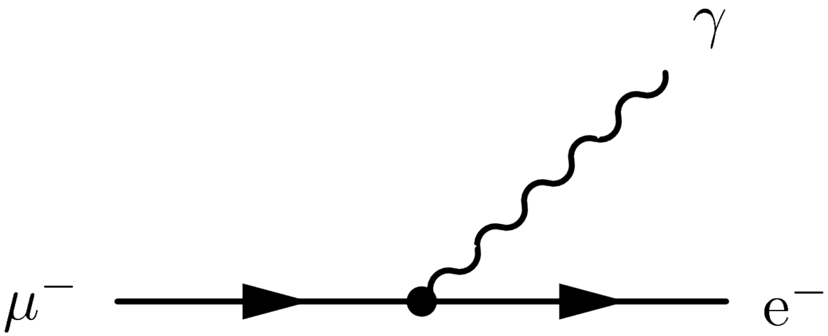


Leptoquarks

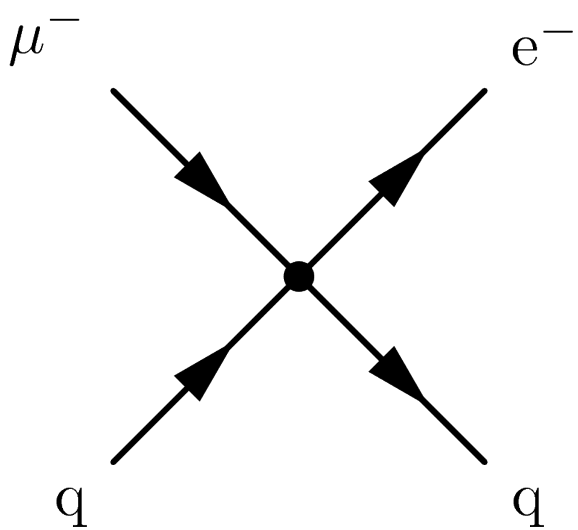
The discovery of Weak scale SUSY at LHC would imply observable cLFV rates

$$R_{\mu e} \sim 10^{-15}$$

We can parameterize all these models in terms of two effective interactions



Active at a common energy scale Λ



A dimension 5 dipole interaction

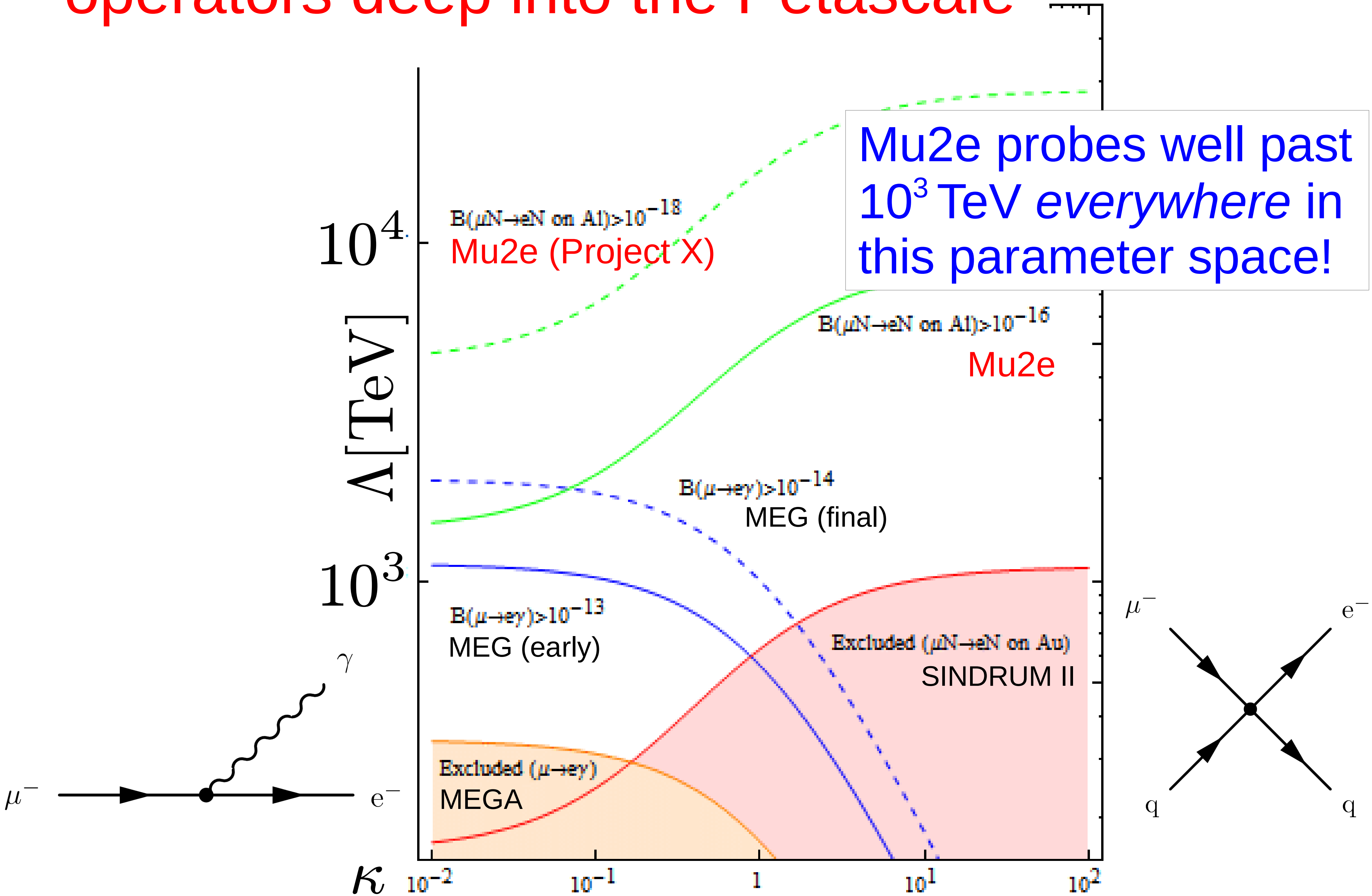
$$\frac{1}{\kappa + 1}$$

And we'll set their relative strength with a dimensionless interpolating factor κ

$$\frac{\kappa}{\kappa + 1}$$

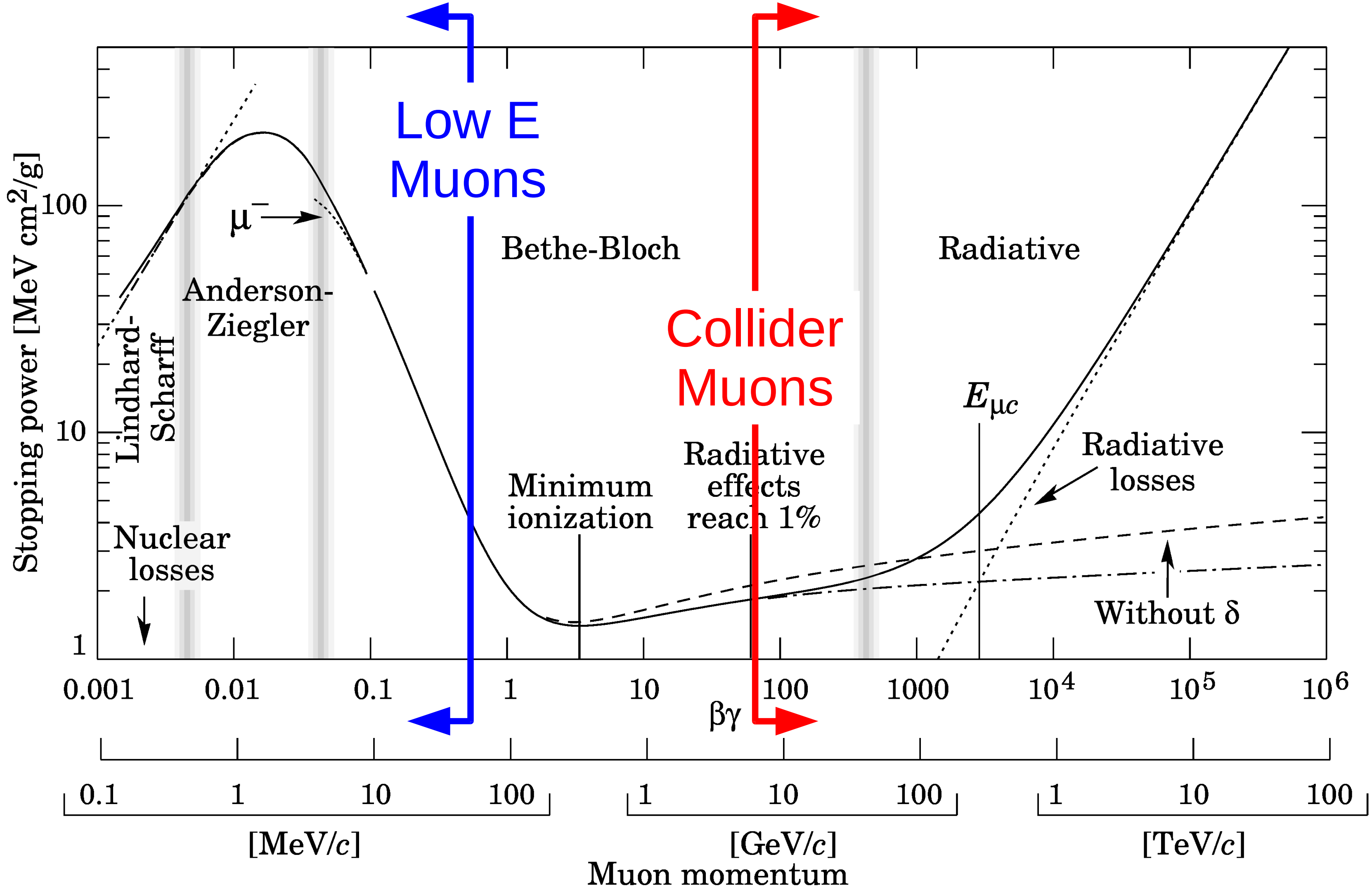
A dimension 6 contact interaction

Mu2e probes combinations of these operators deep into the Petascale



Mu2e probes well past 10^3 TeV *everywhere* in this parameter space!

Our muons are not like your muons...



Negative muons rapidly stop, capture on atoms, and cascade to the 1s state.

$$E_{1s} = -Z^2 2.7\,\mathrm{keV}$$